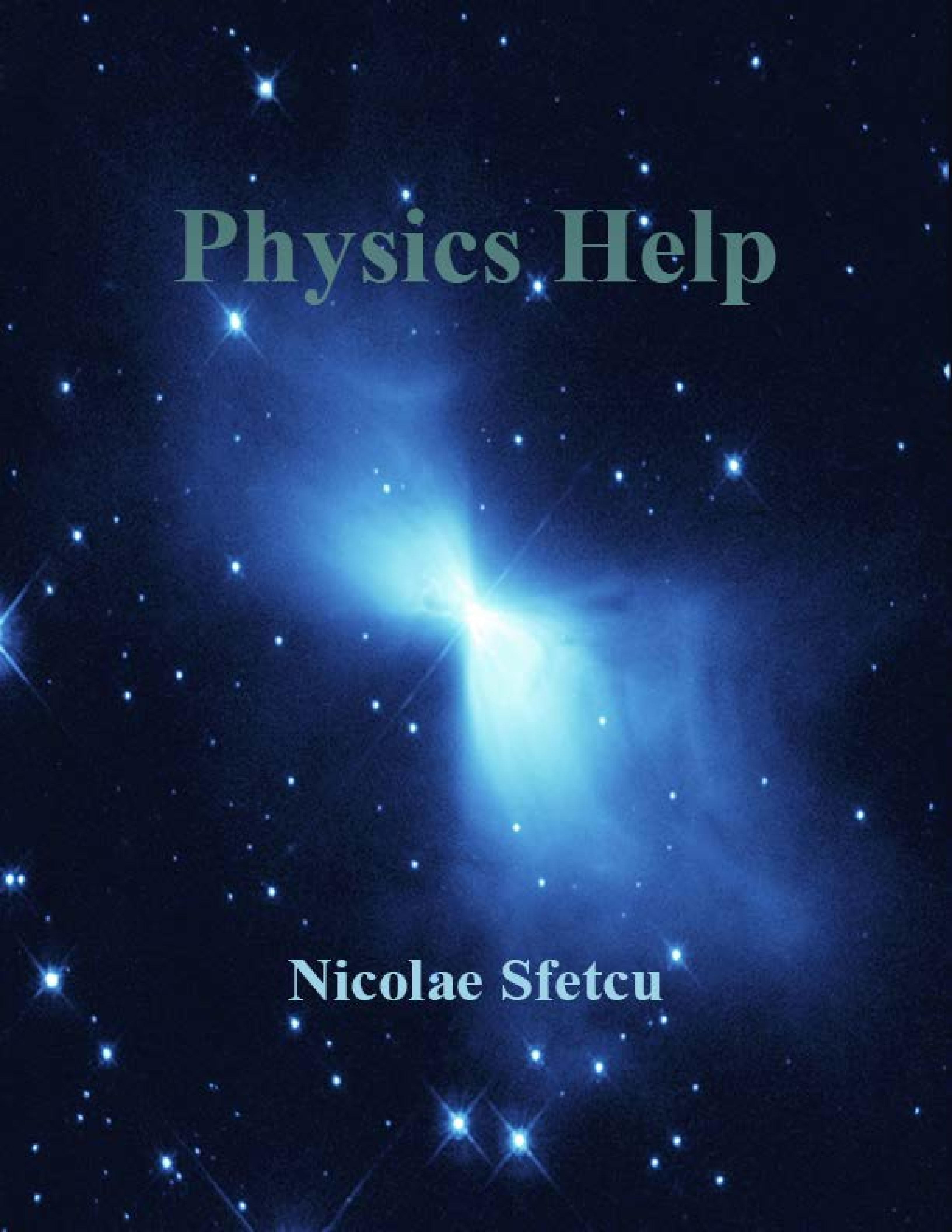
Physics Help



Nicolae Sfetcu

Physics Help

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Published by Nicolae Sfetcu

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Physics

Physics (from Greek from ÆÅÃ¹ºÌÂ (*phusikos*): *natural*, from ÆÍÃ¹Â (*fysis*): Nature) is the science of Nature in the broadest sense. Physicists study the behaviour and interactions of matter and radiation. Theories of physics are generally expressed as mathematical relations. Well-established theories are often referred to as *physical laws* or laws of physics; however, like all scientific theories, they are ultimately provisional.

Physics is very closely related to the other natural sciences, particularly chemistry, the science of molecules and the chemical compounds that they form in bulk. Chemistry draws on many fields of physics, particularly quantum mechanics, thermodynamics and electromagnetism. However, chemical phenomena are sufficiently varied and complex that chemistry is usually regarded as a separate discipline.

Below is an overview of the major subfields and concepts in physics, followed by a brief outline of the history of physics and its subfields.

A brief history of physics

Note: The following is a cursory overview of the development of physics. For a more detailed history, please refer to the main article on this subject, History of physics.

Since antiquity, people have tried to understand the behavior of matter: why unsupported objects drop to the ground, why different materials have different properties, and so forth. Also a mystery was the character of the universe, such as the form of the Earth and the behavior of celestial objects such as the Sun and the Moon. Several theories were proposed, most of them were wrong. These theories were largely couched in philosophical terms, and never verified by systematic experimental testing. There were exceptions and there are anachronisms: for example, the Greek thinker Archimedes derived many correct quantitative descriptions of mechanics and hydrostatics.

During the late 16th century, Galileo pioneered the use of experiment to validate physical theories, which is the key idea in the scientific method. Galileo formulated and successfully tested several results in dynamics, in particular the Law of Inertia. In 1687, Newton published the Principia Mathematica, detailing two comprehensive and successful physical theories: Newton's laws of motion, from which arise classical mechanics; and Newton's Law of Gravitation, which describes the fundamental force of gravity. Both theories agreed well with experiment. Classical mechanics would be exhaustively extended by Lagrange, Hamilton, and others, who produced new formulations, principles, and results. The Law of Gravitation initiated the field of astrophysics, which describes astronomical phenomena using physical theories.

From the 18th century onwards, thermodynamics was developed by Boyle, Young, and many others. In 1733, Bernoulli used statistical arguments with classical mechanics to derive thermodynamic results, initiating the field of statistical mechanics. In 1798, Thompson demonstrated the conversion of mechanical work into heat, and in 1847 Joule stated the law of conservation of energy, in the form of heat as well as mechanical energy.

The behavior of electricity and magnetism was studied by Faraday, Ohm, and others. In 1855, Maxwell unified the two phenomena into a single theory of electromagnetism,

described by Maxwell's equations. A prediction of this theory was that light is an electromagnetic wave.

In 1895, Roentgen discovered X-rays, which turned out to be high-frequency electromagnetic radiation. Radioactivity was discovered in 1896 by Henri Becquerel, and further studied by Pierre Curie and Marie Curie and others. This initiated the field of nuclear physics.

In 1897, Thomson discovered the electron, the elementary particle which carries electrical current in circuits. In 1904, he proposed the first model of the atom, known as the plum pudding model. (The existence of the atom had been proposed in 1808 by Dalton.)

In 1905, Einstein formulated the theory of special relativity, unifying space and time into a single entity, spacetime. Relativity prescribes a different transformation between reference frames than classical mechanics; this necessitated the development of relativistic mechanics as a replacement for classical mechanics. In the regime of low (relative) velocities, the two theories agree. In 1915, Einstein extended special relativity to explain gravity with the general theory of relativity, which replaces Newton's law of gravitation. In the regime of low masses and energies, the two theories agree.

In 1911, Rutherford deduced from scattering experiments the existence of a compact atomic nucleus, with positively charged constituents dubbed protons. Neutrons, the neutral nuclear constituents, were discovered in 1932 by Chadwick.

Beginning in 1900, Planck, Einstein, Bohr, and others developed quantum theories to explain various anomalous experimental results by introducing discrete energy levels. In 1925, Heisenberg and 1926, Schrödinger and Dirac formulated quantum mechanics, which explained the preceding quantum theories. In quantum mechanics, the outcomes of physical measurements are inherently probabilistic; the theory describes the calculation of these probabilities. It successfully describes the behavior of matter at small distance scales.

Quantum mechanics also provided the theoretical tools for condensed matter physics, which studies the physical behavior of solids and liquids, including phenomena such as crystal structures, semiconductivity, and superconductivity. The pioneers of condensed matter physics include Bloch, who created a quantum mechanical description of the behavior of electrons in crystal structures in 1928.

During World War II, research was conducted by each side into nuclear physics, for the purpose of creating a nuclear bomb. The German effort, led by Heisenberg, did not succeed, but the Allied Manhattan Project reached its goal. In America, a team led by Fermi achieved the first man-made nuclear chain reaction in 1942, and in 1945 the world's first nuclear explosive was detonated at Trinity site, near Alamogordo, New Mexico.

Quantum field theory was formulated in order to extend quantum mechanics to be consistent with special relativity. It achieved its modern form in the late 1940s with work by Feynman, Schwinger, Tomonaga, and Dyson. They formulated the theory of quantum electrodynamics, which describes the electromagnetic interaction.

Quantum field theory provided the framework for modern particle physics, which studies fundamental forces and elementary particles. In 1954, Yang and Mills developed a class of gauge theories, which provided the framework for the Standard Model. The Standard Model, which was completed in the 1970s, successfully describes almost all elementary particles observed to date.

Future directions

As of 2003, research is progressing on a large number of fields of physics.

In condensed matter physics, the biggest unsolved theoretical problem is the explanation for high-temperature superconductivity. Strong efforts, largely experimental, are being put into making workable spintronics and quantum computers.

In particle physics, the first pieces of experimental evidence for physics beyond the Standard Model have begun to appear. Foremost amongst this are indications that neutrinos have non-zero mass. These experimental results appear to have solved the long-standing solar neutrino problem in solar physics. The physics of massive neutrinos is currently an area of active theoretical and experimental research. In the next several years, particle accelerators will begin probing energy scales in the TeV range, in which experimentalists are hoping to find evidence for the higgs boson and supersymmetric particles.

Theoretical attempts to unify quantum mechanics and general relativity into a single theory of quantum gravity, a program ongoing for over half a century, has yet to bear fruit. The current leading candidates are M-theory and loop quantum gravity.

Many astronomical phenomena have yet to be explained, including the existence of ultra-high energy cosmic rays and the anomalous rotation rates of galaxies. Theories that have been proposed to resolve these problems include doubly-special relativity, modified Newtonian dynamics, and the existence of dark matter. In addition, the cosmological predictions of the last several decades have been contradicted by recent evidence that the expansion of the universe is accelerating.

See unsolved problems in physics for a fuller treatment of this subject.

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Theoretical physics

Theoretical physics attempts to understand the world by making a model of reality, used for rationalizing, explaining, predicting physical phenomena through a "*physical theory*". There are three types of theories in physics; mainstream theories, proposed theories and fringe theories.

Some physical theories are backed by observation, whereas others are not. A physical theory is a model of physical events and cannot be proved from basic axioms. A physical theory is different from a mathemeatical theorem. Physical theories model reality and are a statement of what has been observed, and provide predictions of new observations.

Physical theories can become accepted if they are able to make correct predictions and avoid incorrect ones. Physical theories which are simplier tend to be accepted over theories which are complex. Physical theories are more likely to be accepted if they connect a wide range of phenonomena. The process of testing a physical theory is part of the scientific method.

Mainstream theories

Mainstream theories (sometimes refered to as *central theories*) are the body of knowledge of both factual and scientific views and possess a usual scientific quqality of the tests of repeatability, consistency with existing well-established science and experimentation.

Examples of mainstream physical theories:

Classical mechanics -- Condensed matter physics -- Dynamics (mechanics) -- Electromagnetism -- Field theory -- Fluid mechanics -- General relativity -- Particle physics -- Quantum mechanics -- Quantum field theory -- Solid state physics and the Electronic Structure of Materials -- Special relativity -- Standard Model -- Statistical mechanics -- Thermodynamics

Proposed theories

The proposed theories of physics are relatively new theories which deal with the study of physics which include scientific approaches, means for determining the validity of models and new types of reasoning used to arrive at the theory. Proposed theories can include fringe theories in the process of becoming established (and, sometimes, gaining wider acceptance). Proposed theories usually have not been tested.

Examples of proposed physical theories:

Dynamic theory of gravity -- Creationism -- Emergence -- Grand unification theory -- Loop quantum gravity -- M-theory -- Plasma Universe -- String theory -- Theory of everything

Fringe theories

Fringe theories include any new area of scientific endeavor in the process of becoming established and some proposed theories. It can include speculative sciences. This includes physics fields and physical theories presented in accordance with known evidence, and a body of associated predictions have been made according to that theory.

Some fringe theories go on to become an widely accepted part of physics. Other fringe theories end up being disproven. Some fringe theories are a form of protoscience and others are a form of pseudoscience. The falsification of the original theory sometimes leads to reformulation of the theory.

Examples of fringe physical theories:

Cold fusion -- Dynamic theory of gravity -- Grand unification theory -- Loop quantum gravity -- Luminiferous aether -- Orgone energy -- Reciprocal System of Theory -- Steady state theory -- Theory of everything

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Central theories

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Classical mechanics

Classical mechanics is the physics of forces, acting upon bodies. It is often referred to as "**Newtonian mechanics**" after Newton and his laws of motion. Classical mechanics is subdivided into statics (which deals with objects in equilibrium) and dynamics (which deals with objects in motion).

Classical mechanics produces very accurate results within the domain of everyday experience. It is superseded by relativistic mechanics for systems moving at large velocities near the speed of light, quantum mechanics for systems at small distance scales, and relativistic quantum field theory for systems with both properties. Nevertheless, classical mechanics is still very useful, because (i) it is much simpler and easier to apply than these other theories, and (ii) it has a very large range of approximate validity. Classical mechanics can be used to describe the motion of human-sized objects (such as tops and baseballs), many astronomical objects (such as planets and galaxies), and even certain microscopic objects (such as organic molecules.)

Although classical mechanics is roughly compatible with other "classical" theories such as classical electrodynamics and thermodynamics, there are inconsistencies that were discovered in the late 19th century that can only be resolved by more modern physics. In particular, classical nonrelativistic electrodynamics predicts that the speed of light is a constant relative to an aether medium, a prediction that is difficult to reconcile with classical mechanics and which led to the development of special relativity. When combined with classical thermodynamics, classical mechanics leads to the Gibbs paradox in which entropy is not a well-defined quantity and to the ultraviolet catastrophe in which a blackbody is predicted to emit infinite amounts of energy. The effort at resolving these problems led to the development of quantum mechanics.

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Description of the theory

We will now introduce the basic concepts of classical mechanics. For simplicity, we only deal with a *point particle*, which is an object with negligible size. The motion of a point particle is characterized by a small number of parameters: its position, mass, and the forces applied on it. We will discuss each of these parameters in turn.

In reality, the kind of objects which classical mechanics can describe always have a non-zero size. True point particles, such as the electron, are properly described by quantum mechanics. Objects with non-zero size have more complicated behavior than our hypothetical point particles, because their internal configuration can change - for example, a baseball can spin while it is moving. However, we will be able to use our results for point particles to study such objects by treating them as composite objects, made up of a large number of interacting point particles. We can then show that such composite objects behave like point particles, provided they are small compared to the distance scales of the problem, which indicates that our use of point particles is self-consistent.

Position and its derivatives

The *position* of a point particle is defined with respect to an arbitrary fixed point in space, which is sometimes called the *origin*, **O**. It is defined as the vector **r** from **O** to the particle. In general, the point particle need not be stationary, so **r** is a function of *t*, the time elapsed since an arbitrary initial time. The *velocity*, or the rate of change of position with time, is defined as

$$\mathbf{v} = \frac{d\mathbf{r}}{dt}.$$

The *acceleration*, or rate of change of velocity, is

$$\mathbf{a} = \frac{d\mathbf{v}}{dt}.$$

The acceleration vector can be changed by changing its magnitude, changing its direction, or both. If the magnitude of **v** decreases, this is sometimes referred to as *deceleration*; but generally any change in the velocity, including deceleration, is simply referred to as acceleration.

Forces; Newton's Second Law

Newton's second law relates the mass and velocity of a particle to a vector quantity known as the force. Suppose *m* is the mass of a particle and **F** is the vector sum of all applied forces (i.e. the *net* applied force.) Then Newton's second law states that

$$\mathbf{F} = \frac{d(m\mathbf{v})}{dt}.$$

The quantity *m***v** is called the momentum. Typically, the mass *m* is constant in time, and Newton's law can be written in the simplified form

$$\mathbf{F} = m\mathbf{a}$$

where **a** is the acceleration, as defined above. It is not always the case that *m* is independent of *t*. For example, the mass of a rocket decreases as its propellant is ejected. Under such circumstances, the above equation is incorrect and the full form of Newton's second law must be used.

Newton's second law is insufficient to describe the motion of a particle. In addition, we require a description of **F**, which is to be obtained by considering the particular physical entities with which our particle is interacting. For example, a typical resistive force may be modelled as a function of the velocity of the particle, say

$$\mathbf{F}_{\mathrm{R}} = -\lambda \mathbf{v}$$

with » a positive constant. Once we have independent relations for each force acting on a particle, we can substitute it into Newton's second law to obtain an ordinary differential equation, which is called the *equation of motion*. Continuing our example, suppose that friction is the only force acting on the particle. Then the equation of motion is

$$-\lambda \mathbf{v} = m\mathbf{a} = m\frac{d\mathbf{v}}{dt}.$$

This can be integrated to obtain

$$\mathbf{v} = \mathbf{v}_0 e^{-\lambda t/m}$$

where $\mathbf{v}_0$ is the initial velocity. This means that the velocity of this particle decays exponentially to zero as time progresses. This expression can be further integrated to obtain the position **r** of the particle as a function of time.

Important forces include the gravitational force and the Lorentz force for electromagnetism. In addition, Newton's third law can sometimes be used to deduce the forces acting on a particle: if we know that particle A exerts a force **F** on another particle B, it follows that B must exert an equal and opposite *reaction force*, -**F**, on A.

Energy

If a force **F** is applied to a particle that achieves a displacement ´**r**, the *work done* by the force is the scalar quantity

$$\delta W = \mathbf{F} \cdot \delta \mathbf{r}.$$

Suppose the mass of the particle is constant, and ´W_{total} is the total work done on the particle, which we obtain by summing the work done by each applied force. From Newton's second law, we can show that

´W_{total} = ´T,

where *T* is called the kinetic energy. For a point particle, it is defined as

$$T = \frac{m|\mathbf{v}|^2}{2}.$$

For extended objects composed of many particles, the kinetic energy of the composite body is the sum of the individual particles' kinetic energies.

A particular class of forces, known as *conservative forces*, can be expressed as the gradient of a scalar function, known as the potential energy and denoted *V*:

$$\mathbf{F} = -\nabla V.$$

Suppose all the forces acting on a particle are conservative, and V is the total potential energy, obtained by summing the potential energies corresponding to each force. Then

$$\mathbf{F} \cdot \delta\mathbf{r} = -\nabla V \cdot \delta\mathbf{r} = -\delta V$$

$$\Rightarrow -\delta V = \delta T$$

$$\Rightarrow \delta(T + V) = 0.$$

This result is known as the *conservation of energy*, and states that the total energy, $E = T + V$, is constant in time. It is often useful, because most commonly encountered forces are conservative.

Further results

Newton's laws provide many important results for composite bodies. See angular momentum.

There are two important alternative formulations of classical mechanics: Lagrangian mechanics and Hamiltonian mechanics. They are equivalent to Newtonian mechanics, but are often more useful for solving problems. These, and other modern formulations, usually bypass the concept of "force", instead referring to other physical quantities, such as energy, for describing mechanical systems.

History

The Greeks and Aristotle in particular were the first to propose that there are abstract principles governing nature.

One of the first scientists who suggested abstract laws was Galileo Galilei who also performed the famous experiment of dropping two canon balls from the tower of Pisa (The theory, and the practice showed that they both hit the ground at the same time).

Sir Isaac Newton was the first to propose the three laws of motion (the law of inertia, the second law mentioned above, and the law of action and reaction), and to prove that these laws govern both everyday objects and celestial objects.

Newton also developed the calculus which is necessary to perform the mathematical calculations involved in classical mechanics.

After Newton the field became more mathematical and more abstract.

Further Reading

- Feynman, R., *Six Easy Pieces*.
- ---, *Six Not So Easy Pieces*.
- ---, *Lectures on Physics*.
- Kleppner, D. and Kolenkow, R. J., *An Introduction to Mechanics*, McGraw-Hill (1973).

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Thermodynamics

Thermodynamics is the study of energy, its conversions between various forms such as heat, and the ability of energy to do work. It is closely related to statistical mechanics from which many themodynamic relationships can be derived.

It can be argued that thermodynamics was misnamed as it does not actually relate to rates of change as such and therefore would probably have been better called thermostatics as a field. Thermodynamics relates to whether certain chemical reactions are possible but not how quickly they occur.

The field covers a wide range of topics including, but not limited to: efficiency of heat engines and turbines, phase equilibria, PVT relationships. gas laws (both ideal and non ideal), energy balances, heats of reactions, and combustion reactions. It is governed by 4 basic laws (in brief):

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The Laws of Thermodynamics

Alternative statements are given for each law. These statements are, for the most part, mathematically equivalent.

- Zeroth law: A fundamental concept within thermodynamics, however, it was not termed a law until after the first three laws were already widely in use, hence the zero numbering. There is some discussion about its status. Stated as:
  - If each of two systems is in thermal equilibrium with a third system, all must be in equilibrium with each other.
- 1st Law: Is stated as follows:
  - Energy can neither be created nor destroyed only changed.
  - The heat flowing into a system equals the sum of change in internal energy plus the work done by the system.

        - The work exchanged in an adiabatic process depends only on the initial and the final state and not on the details of the process.
        - The sum of heat flowing into a system and work done by the system is zero.
- 2nd Law: A far reaching and powerful law, it can be stated many ways, the most popular of which is:
    - It is impossible to obtain a process such that the unique effect is the subtraction of a positive heat from a reservoir and the production of a positive work.
        - A system operating in contact with a thermal reservoir cannot produce positive work in its surroundings (Kelvin)
        - A system operating in a cycle cannot produce a positive heat flow from a colder body to a hotter body (Clausius)
    - The entropy of a closed system never decreases (see Maxwell's demon)
- 3rd Law: This law explains why it is so hard to cool something to absolute zero:
    - All processes cease as temperature approaches zero.
    - As temperature goes to 0, the entropy of a system approaches a constant

The three original laws have been humorously summarised as: (1) you can't win; (2) you can't break even; (3) you can't get out of the game.

Basics

This is a brief summary and collection of the major concepts in thermodynamics. To learn more about each, just click on the corresponding links:

U stands for the internal energy, T stands for temperature, S stands for entropy, P stands for pressure, V stands for volume, Á stands for density, F stands for Helmholtz free energy, H stands for enthalpy, G stands for Gibbs free energy, ¼ stands for chemical potential and N stands for particle number.

The rest of this discussion is about systems in equilibrium only. For nonequilibrium thermodynamics, see ...

Substances describable by temperature alone

Blackbody radiation is an example. The reason why this is the case is because photon number isn't conserved. The state is completely described by its temperature except at phase transitions and perhaps spontaneous symmetry breaking in the ordered phase. given the internal energy as a function of temperature, we can define F=U-TS.

Substances describable by temperature and pressure alone

Most "pure" nonmagnetic substances fall into this category. This state is completely described by its temperature and pressure, except at phase transitions and perhaps spontaneous symmetry breaking in the ordered phase. Given U and V (or the density Á) as a function of T and P, we can define the Helmholtz energy as before and the Gibbs energy as G=U-TS+PV and the enthalpy as H=U+PV.

Substances describable by temperature, pressure and chemical potential

If there are more than one kind of atom/molecule, a substance would fall into this category. This state is completely described by its temperature, pressure and chemical potentials, except at phase transitions and perhaps spontaneous symmetry breaking in the ordered phase.

Substances describable by temperature and magnetic field

If a substance is a ferromagnet or a superconductor, for example, it would fall into this category. It is completely described by its temperature and magnetic field, except at phase transitions and perhaps spontaneous symmetry breaking in the ordered phase.

Links

- Entropy
- Temperature

Thermodynamic Systems

A thermodynamic system is that part of the universe that is under consideration. A real or imaginary boundary separates the system from the rest of the universe, which is referred to as the surroundings. Often thermodynamic systems are characterized by the nature of this boundary as follows:

- Isolated systems are completely isolated from their surroundings. Neither heat nor matter can be exchanged between the system and the surroundings. An example of an isolated system would be an insulated container, such as an insulated gas cylinder. (In reality, a system can never be absolutely isolated from its environment, because there is always at least some slight coupling, even if only via minimal gravitational attraction).
- Closed systems are separated from the surroundings by an impermeable barrier. Heat can be exchanged between the system and the surroundings, but matter cannot. A greenhouse is an example of a closed system.
- Open systems can exchange both heat and matter with their surroundings. Portions of the boundary between the open system and its surroundings may be impermeable and/or adiabatic, however at least part of this

boundary is subject to heat and mass exchange with the surroundings. The ocean would be an example of an open system.

Thermodynamic State

A key concept in thermodynamics is the *state of a system*. When a system is at equilibrium under a given set of conditions, it is said to be in a definite *state*. For a given thermodynamic state, many of the system's properties have a specific value corresponding to that state. The values of these properties are a function of the state of the system and are independent of the path by which the system arrived at that state. The number of properties that must be specified to describe the state of a given system is given by Gibbs phase rule. Since the state can be described by specifying a small number of properties, while the values of many properties are determined by the state of the system, it is possible to develop relationships between the various state properties. One of the main goals of Thermodynamics is to understand these relationships between the various state properties of a system. Equations of State are examples of some of these relationships.

Thermodynamics also touches upon the fields of:

- Fluid mechanics
- Calorimetry
- Thermal Analysis
- Thermochemistry also known as chemical thermodynamics

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Statistical mechanics

Statistical mechanics is the application of statistics, which includes mathematical tools for dealing with large populations, to the field of Mechanics, which is concerned with the motion of particles or objects when subjected to a force. It provides a framework for relating the microscopic properties of individual atoms and molecules to the macroscopic or bulk properties of materials that can be observed in every day life, therefore explaining thermodynamics as a natural result of statistics and mechanics (classical and quantum). In particular, it can be used to calculate the thermodynamic properties of bulk materials from the spectroscopic data of individual molecules.

At the heart of statistical mechanics is the partition function (see Derivation of the partition function):

$$Z = \sum_i \exp\left(\frac{-E_i}{kT}\right)$$

where k is Boltzmann's constant, T is the temperature and E_i reflects each possible energetic state of the system. This is the version for systems which don't allow an exchange of matter. Otherwise, we would have to introduce chemical potentials, ¼$_j$, j=1,...,n and replace the partition function with

$$Z = \sum_i \exp\left(\frac{\sum_{j=1}^n \mu_j N_{ij} - E_i}{kT}\right)$$

where N_{ij} is the number of j^{th} species particles in the i^{th} configuration. Sometimes, we also have other variables to add to the partition function, one corresponding to each conserved quantity. Most of them, however, can be safely interpreted as chemical potentials. For the rest of this article, we will ignore this complication and pretend chemical potentials don't matter.

The partition function provides a measure of the total number of energetic states available to the system at a given temperature. Similarly,

$$\exp\left(\frac{-E_i}{kT}\right)$$

provides a measure of the number of energetic states of a particular energy that are likely to be occupied at a given temperautre.

Dividing the second equation by the first equation gives the probability of finding the system in a particular energetic state, *i*:

$$p_i = \frac{\exp(-E_i/kT)}{Z}$$

This probability can be used to find the average value, which corresponds to the macroscopic value, of any property, *J*, that depends on the energetic state of the system by using the formula:

$$\langle J \rangle = \sum_i p_i J_i = \sum_i J_i \frac{\exp(-E_i/kT)}{Z}$$

where < *J* > is the average value of property *J*. This equation can be applied to the internal energy, *U*, and pressure, *P*:

$$U = \sum_i E_i \frac{\exp(-E_i/kT)}{Z}$$

$$P = \sum_i P_i \frac{\exp(-E_i/kT)}{Z}$$

Subsequently, these equations can be combined with known thermodynamic relationships between *U* and *P* to arrive at an expression for *P* in terms of only temperature, volume and the partition function. Similar relationships in terms of the partition function can be derived for other thermodynamic properties as shown in the following table.

Helmholtz free energy: $A = -kT\ln Z$

Internal energy: $U = kT^2 \left(\frac{d\ln Z}{dT}\right)_{N,V}$

Pressure: $P = kT \left(\frac{d\ln Z}{dV}\right)_{N,T}$

Entropy: $S = k\ln Z + U / T$

Gibbs free energy: $G = -kT \ln Z + kTV \left(\frac{d \ln Z}{dV}\right)_{N,T}$

Enthalpy: $H = U + PV$

Constant Volume Heat Capacity: $C_V = \left(\frac{dU}{dT}\right)_{N,V}$

Constant Pressure Heat Capacity: $C_P = \left(\frac{dH}{dT}\right)_{N,P}$

Chemical potential: $\mu_i = -kT \left(\frac{d \ln Z}{dN_i}\right)_{T,V,N}$

It is often useful to consider the energy of a given molecule to be distributed among a number of modes. For example, translational energy refers to that portion of energy associated with the motion of the center of mass of the molecule. Configurational energy refers to that portion of energy associated with the various attractive and repulsive forces between molecules in a system. The other modes are all considered to be internal to each molecule. They include rotational, vibrational, electronic and nuclear modes. If we assume that each mode is independent (a very questionable assumption!!!!!) the total energy can be expressed as the sum of each of the components:

$$E = E_t + E_c + E_n + E_e + E_r + E_v$$

Where the subscripts t, c, n, e, r, and v correspond to translational, configurational, nuclear, electronic, rotational and vibrational modes, respectively. The relationship in this equation can be substituted into the very first equation to give:

$$Z = \sum_i \exp\left(-\frac{E_{ti} + E_{ci} + E_{ni} + E_{ei} + E_{ri} + E_{vi}}{kT}\right)$$

$$= \sum_i \exp\left(\frac{-E_{ti}}{kT}\right) \exp\left(\frac{-E_{ci}}{kT}\right) \exp\left(\frac{-E_{ni}}{kT}\right) \exp\left(\frac{-E_{ei}}{kT}\right) \exp\left(\frac{-E_{ri}}{kT}\right) \exp\left(\frac{-E_{vi}}{kT}\right)$$

$= Z_t Z_c Z_n Z_e Z_r Z_v$

Thus a partition function can be defined for each mode. Simple expressions have been derived relating each of the various modes to various measurable molecular properties, such as the characteristic rotational or vibrational frequencies.

Expressions for the various molecular partition functions are shown in the following table.

Nuclear $Z_n = 1 \qquad (T < 10^8 K)$

Electronic $Z_e = W_0 \exp(kTD_e + W_1 \exp(-\theta_{e1}/T) + \cdots)$

vibrational $Z_v = \prod_j \frac{\exp(-\theta_{vj}/2T)}{1 - \exp(-\theta_{vj}/T)}$

rotational (linear) $Z_r = \frac{T}{\sigma}\theta_r$

rotational (non-linear) $Z_r = \sqrt{\frac{\pi}{\sigma}\frac{T^3}{\theta_A\theta_B\theta_C)^{1/2}}}$

Translational $Z_t = \frac{(2\pi mkT)^{3/2}}{h^3}$

Configurational (ideal gas) $Z_c = V$

These equations can be combined with those in the first table to determine the contribution of a particular energy mode to a thermodynamic property. For example the "rotational pressure" could be determined in this manner. The total pressure could be found by summing the pressure contributions from all of the individual modes, ie:

$$P = P_t + P_c + P_n + P_e + P_r + P_v$$

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Electromagnetism

Electromagnetism is a theory unified by James Clerk Maxwell to explain the interrelationship between electricity and magnetism. At the heart of this theory is the notion of an electromagnetic field.

A stationary electromagnetic field stays bound to its origin. Examples of stationary fields are: the magnetic field around a wire carrying current or the electric field between the plates of a capacitor.

A changing electromagnetic field propagates away from its origin in the form of a wave. These waves travel in vacuum at the speed of light and exist in a wide spectrum of wavelengths. Examples of the dynamic fields of electromagnetic radiation (in order of increasing frequency): radio waves, microwaves, light (infrared, visible light and ultraviolet), x-rays and gamma rays. In the field of particle physics this electromagnetic radiation is the manifestation of the electromagnetic interaction between charged particles.

The subfield of electromagnetism dealing specifically with the rapidly changing electric and magnetic fields which constitute light, is called electrodynamics.

The whole of electromagnetism is governed by Maxwell's equations, which are compatible with and served as a motivation for the theory of relativity.

Mathematical Description

The electromagnetic field exerts the following force (often called the Lorentz force) on charged particles:

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

$$\mathbf{F} = q\mathbf{E} + q\frac{\mathbf{v}}{c} \times \mathbf{B}$$

in Gauss units,

where all boldfaced quantities are vectors: **F** is the force that a charge q experiences, **E** is the electric field at q's location, **v** is q's velocity, **B** is the strength of the magnetic field at q's position, and c is the speed of light.

This description of the force between charged particles, unlike Coulomb's force law, does not break down under relativity and in fact, the magnetic force is seen as part of the relativistic interaction of fast moving charges that Coulomb's law neglects.

The Electric Field E

The electric field **E** is defined such that, on a stationary charge:

$$\mathbf{F} = q_o\mathbf{E}$$

where q_o is what is known as a test charge. The size of the charge doesn't really matter, as long as it is small enough as to not influence the electric field by its mere presence. What is plain from this definition, though, is that the unit of **E** is N/C, or newtons per coulomb. This unit is equal to V/m (volts per meter), see below.

The above definition seems a little bit circular, but in electrostatics, where charges are not moving, Coulomb's law works fine. So what we end up with is:

$$\mathbf{E} = \sum_{i=1}^{n} \frac{q_i\left(\mathbf{r}-\mathbf{r}_i\right)}{4\pi\epsilon_o\left|\mathbf{r}-\mathbf{r}_i\right|^3}$$

where n is the number of charges, q_i is the amount of charge associated with the 'i'th charge, $\mathbf{r}_i$ is the position of the 'i'th charge, **r** is the position where the electric field is being determined, and μ_o is a universal constant called the permittivity of free space.

Note: the above is just Coulomb's law, divided by q_1, added up more multiple charges.

Changing the summation to an integral yields the following:

$$E = \int \rho\mathbf{r}_{unit}(4\pi\epsilon_o r^2)^{-1}dV$$

where Á is the charge density as a function of position, $\mathbf{r}_{unit}$ is the unit vector pointing from dV to the point in space **E** is being calculated at, and r is the distance from the point **E** is being calculated at to the point charge.

Both of the above equations are cumbersome, especially if one wants to calculate **E** as a function of position. There is, however, a scalar function called the electrical potential that can help. Electric potential, also called voltage (the units for which are the volt), which is defined thus:

$$\phi_{\mathbf{E}} = -\int_s \mathbf{E}\cdot d\mathbf{s}$$

where $Æ_E$ is the electric potential, and s is the path over which the integral is being taken.

Unfortunately, this definition has a caveat. In order for a potential to exist $\nabla \times \mathbf{E}$ must be zero. Whenever the charges are stationary, however, this condition will be met, and finding the field of a moving charge simply requires a relativistic transform of the electric field.

From the definition of charge, it is trivial to show that the electric potential of a point charge as a function of position is:

$$\phi = q(4\pi\epsilon_o\left|\mathbf{r}-\mathbf{r}_q\right|)^{-1}$$

where q is the point charge's charge, **r** is the position, and $\mathbf{r}_q$ is the position of the point charge. The potential for a general distribution of charge ends up being:

$$\phi = (4\pi\epsilon_o)^{-1}\int \rho r^{-1} dV$$

where Á is the charge density as a function of position, and r is the distance from the volume element dV.

Note well that Æ is a scalar, which means that it will add to other potential fields as a scalar. This makes it relatively easy to break complex problems down in to simple parts and add their potentials. Getting the electric field from the potential is just a matter of taking the definition of Æ backwards:

$$\mathbf{E} = -\nabla\phi$$

From this formula it is clear that **E** can be expressed in V/m (volts per meter).

Electromagnetic Method

A geophysical method in which the magnetic and or electric fields resulting from generated surface currents are measured. Measurements may be made in the frequency domain at a number of frequencies, or the time domain at several time intervals after a transient pulse. Natural field methods such as magnetotellurics (MT) use natural magnetic and electromagnetic field as the source.

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Special relativity

The **special theory of relativity (SR)** is the physical theory published in 1905 by Albert Einstein that modified Newtonian physics to incorporate electromagnetism as represented by Maxwell's equations. The theory is called "special" because the theory applies only to the special case of measurements made when both the observer and that which is being observed are not affected by gravity. Ten years later, Einstein published the theory of General Relativity, or GR for short, which is the extension of special relativity to incorporate gravitation.

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Motivation for the theory of special relativity

Before the formulation of special relativity, Hendrik Lorentz and others had already noted that electromagnetics differed from Newtonian physics in that observations by one of some phenomenon can differ from those of a person moving relative to that person at speeds nearing the speed of light. For example, one may observe *no* magnetic field, yet another observes a magnetic field in the same physical area. Lorentz suggested an aether theory in which objects and observers travelling with respect to a stationary aether underwent a physical shortening (*Lorentz-Fitzgerald contraction*) and a change in temporal rate (*time dilation*). This allowed the partial reconciliation of electromagnetics and Newtonian physics. When the velocities involved are much less than speed of light, the resulting laws simplify to Newton's laws. The theory, known as *Lorentz Ether Theory* (LET) was criticized (even by Lorentz himself) because of its ad hoc nature.

While Lorentz suggested the Lorentz transformation equations as a mathematical description that accurately described the results of measurements, Einstein's contribution was to *derive* these equations from a more fundamental theory. Einstein wanted to know what was *invariant* (the same) for all observers. His original title for his theory was (translated from German) "Theory of Invariants". It was Max Planck who suggested the term "relativity" to highlight the notion of transforming the laws of physics between observers moving *relative* to one another.

Special relativity is usually concerned with the behaviour of objects and observers which remain at rest or are moving at a constant velocity. In this case, the observer is said to be in an *inertial frame of reference* or simply *inertial*. Comparison of the position and time of events as recorded by different inertial observers can be done by using the Lorentz transformation

equations. A common misstatement about relativity is that SR cannot be used to handle the case of objects and observers who are undergoing acceleration (*non-inertial* reference frames), but this is incorrect. For an example, see the relativistic rocket problem. SR can correctly predict the behaviour of accelerating bodies as long as the acceleration is not due to gravity, in which case general relativity must be used.

Invariance of the speed of light

SR postulated that the speed of light in vacuum is the same to all inertial observers, and said that every physical theory should be shaped or reshaped so that it is the same mathematically for every inertial observer. This postulate (which comes from Maxwell's equations for electromagnetics) together with the requirement, successfully reproduces the Lorentz transformation equations, and has several consequences that struck many people as bizarre, among which are:

- The time lapse between two events is not invariant from observer to another, but is dependent on the relative speeds of the observers' reference frames.
- The twin paradox is the "story" of a twin who flies off in a spaceship travelling near the speed of light. When he returns he discovers that his twin has aged much more rapidly than he has (or he aged more slowly).
- Two events that occur simultaneously in different places in one reference frame may occur one after the other in another reference frame (relativity of simultaneity).
- The dimensions (e.g. length) of an object as measured by an observer may differ from those by another.
- The mass of a particle increases as it's velocity increases. This led to the famous equation $E = mc^2$. See below.

Lack of an absolute reference frame

Another radical consequence is the rejection of the notion of an absolute, unique, frame of reference. Previously it had been suggested that the universe was filled with a substance known as "aether" (absolute space), against which speeds could be measured. Aether had some wonderful properties: it was sufficiently elastic that it could support electromagnetc waves, those waves could interact with matter, yet it offered no resistance to bodies passing through it. The results of various experiments, culminating in the famous Michelson-Morley experiment, suggested that either the Earth was always stationary, or the notion of an absolute frame of reference was mistaken and must be discarded.

Equivalence of mass and energy

Perhaps most far reaching, it also showed that energy and mass, previously considered separate, were equivalent, and related by the most famous expression from the theory:

$$E = mc^2$$

where E is the energy of the body (at rest), m is the mass and c is the speed of light. If the body is moving with speed v relative to the observer, the total energy of the body is:

$$E = {}^{3}mc^2,$$

where

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

(The term ^{3} occurs frequently in relativity, and comes from the Lorentz transformation equations.) It is worth noting that if v is much less than c this can be written as

$$E \approx mc^2 + \frac{1}{2}mv^2$$

which is precisely equal to the "energy of existence", mc^2, and the Newtonian kinetic energy, $mv^2/2$. This is just one example of how the two theories coincide when velocities are small.

At very high speeds, the denominator in the energy equation (2) approaches a value of zero as the velocity approaches c. Thus, at the speed of light, the energy would be infinite, which precludes things that have mass from moving at that speed.

The most practical implication of this theory is that it puts an upper limit to the laws (see Law of nature) of Classical Mechanics and gravity formed by Isaac Newton at the speed of light. Nothing carrying mass can move faster than this speed. As an object's velocity approaches the speed of light, the amount of energy required to accelerate it approaches infinity, making it impossible to reach the speed of light. Only particles with no mass, such as photons, can actually achieve this speed (and in fact they must always travel at this speed in all frames of reference), which is approximately 300,000 kilometers per second or 186,300 miles per second.

The name "tachyon" has been used for hypothetical particles which would move faster than the speed of light, but to date evidence of the actual existence of tachyons has not been produced.

Simultaneity

Special relativity also holds that the concept of simultaneity is relative to the observer: A 'time-like interval' has end-points separated by a path along which it is possible for a hypothetical matter or light to travel. A 'space-like interval' has end-points separated by a path in space-time along which neither light nor any slower-than-light signal could travel. No information can pass between points separated by a space-like interval. Events along a space-like interval cannot influence one another by transmitting light or matter, and would appear simultaneous to an observer in the right frame of reference. To observers in different frames of reference, event A could seem to come before event B or vice-versa; this does not apply to events separated by time-like intervals.

Status of Special Relativity

Special relativity is now universally accepted by the physics community, unlike General Relativity which is still insufficiently confirmed by experiment to exclude certain alternative theories of gravitation. However, there are a handful of people opposed to relativity on various grounds and who have proposed various alternatives, mainly Aether theories. One alternative theory is doubly-special relativity, where a characteristic length is added to the list of invariant quantities.

The Geometry of Space-time in Special Relativity

SR uses a 'flat' 4 dimensional space, usually referred to as space-time. This space, however, is very similar to the standard 3 dimensional Euclidean space, and fortunately by that fact, very easy to work with.

The differential of distance(ds) in cartesian 3D space is defined as:

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2$$

where (dx_1,dx_2,dx_3) are the differentials of the three spatial dimensions. In the geometry of special relativity, a fourth dimension, time, is added, with units of c, so that the equation for the differential of distance becomes:

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2 - c^2dt^2$$

In many situations it may be convenient to treat time as imaginary (e.g. it may simplify equations), in which case t in the above equation is replaced by $i.t'$, and the metric becomes

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2 + c^2(dt')^2$$

If we reduce the spatial dimensions to 2, so that we can represent the physics in a 3-D space,

$$ds^2 = dx_1^2 + dx_2^2 - c^2dt^2$$

We see that the null geodesics lie along a dual-cone defined by the equation

$$ds^2 = 0 = dx_1^2 + dx_2^2 - c^2dt^2$$

, or

$$dx_1^2 + dx_2^2 = c^2dt^2$$

Which is the equation of a circle with $r=c*dt$. If we extend this to three spatial dimensions, the null geodesics are continuous concentric spheres, with radius = distance = c*(+ or -)time.

$$ds^2 = 0 = dx_1^2 + dx_2^2 + dx_3^2 - c^2dt^2$$

$$dx_1^2 + dx_2^2 + dx_3^2 = c^2dt^2$$

This null dual-cone represents the "line of sight" of a point in space. That is, when we look at the stars and say "The light from that star which I am receiving is X years old.", we are

looking down this line of sight: a null geodesic. We are looking at an event $d = \sqrt{x_1^2 + x_2^2 + x_3^2}$ meters away and *d/c* seconds in the past. For this reason the null dual cone is also known as the 'light cone'. (The point in the lower left of the picture below represents the star, the origin represents the observer, and the line represents the null geodesic "line of sight".)

The cone in the *-t* region is the information that the point is 'receiving', while the cone in the *+t* section is the information that the point is 'sending'. We can envision a space of null dual-cones and recall the concept of cellular automata, applying it in a spatially and temporally continuous fashion.

Tests of postulates of special relativity

- Michelson-Morley experiment - ether drift
- Hamar experiment - obstruction of ether flow
- Trouton-Noble experiment - torque on a capacitor
- Kennedy-Thorndike experiment - time contraction
- Forms of the emission theory experiment

Related Topics

Physics and Math:

- Cosmology
- General Relativity

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General relativity

In physics, **general relativity** is the theory of gravitation published by Albert Einstein in 1915. According to general relativity the force of gravity is a manifestation of the local geometry of spacetime. Although the modern theory is due to Einstein, its origins go back to the axioms of Euclidean geometry and the many attempts over the centuries to prove Euclid's fifth postulate, that parallel lines remain always equidistant, culminating with the realisation by Lobachevsky, Bolyai and Gauss that this axiom need not be true. The general mathematics of non-Euclidean geometries was developed by Gauss' student, Riemann, but these were thought to be wholly inapplicable to the real world until Einstein had developed his theory of relativity.

This image is misleading. Spacetime should not be thought of as being embedded in a higher-dimensional flat space with the "weight" of massive objects "stretching" the "trampoline-like spacetime fabric" and trajectories around this "dent" being curved due to the pull of gravity in some higher dimension due to the "slope" of the "trampoline"...

The special theory of relativity (1905) modified the equations used in comparing the measurements made by differently moving bodies, in view of the constant value of the speed of light, i.e. its observed invariance in reference frames moving uniformly relative to each other: this had the consequence that physics could no longer treat space and time separately, but only as a single four-dimensional system, "space-time," which was divided into "time-like" and "space-like" directions differently depending on the observer's motion. The general theory added to this that the presence of matter "warped" the local space-time environment, so that apparently "straight" lines through space and time have the properties we think of "curved" lines as having.

On May 29, 1919 observations by Arthur Eddington of shifted star positions during a solar eclipse confirmed the theory.

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Foundations of Relativity and Special Relativity

This section outlines the major experimental results and mathematical advances that led to the formulation of General Relativity, and also sketches the more limited Special Theory of Relativity.

Gauss had realised that there is no prior reason that the geometry of space should be Euclidean. What this means is that if a physicist holds up a stick, and a cartographer stands some distance away and measures its length by a triangulation technique based on Euclidean geometry, then he is not guaranteed to get the same answer as if the physicist brings the stick to him and he measures its length directly. Of course for a stick he could not in practice measure the difference between the two measurements, but there are equivalent measurements which do detect the non-Euclidean geometry of space-time directly; for example the Pound-Rebka experiment (1959) detected the change in wavelength of light from a cobalt source rising 22.5 meters against gravity in a shaft in the Jefferson Physical Laboratory at Harvard, and the rate of atomic clocks in GPS satellites orbiting the Earth has to be corrected for the effect of gravity.

Newton's theory of gravity had assumed that objects did in fact have absolute velocities: that some things *really* were at rest while others *really* were in motion. He realized, and made clear, that there was no way these absolutes could be measured. All the measurements one can make provide only velocities relative to one's own velocity (positions relative to one's own position, and so forth), and all the laws of mechanics would appear to operate identically no matter how one was moving. Newton believed, however, that the theory could not be made sense of without presupposing that there *are* absolute values, even if they cannot be determined. In fact, Newtonian mechanics can be made to work without this assumption: the

outcome is rather innocuous, and should not be confused with Einstein's relativity which further requires the constancy of the speed of light.

In the nineteenth century Maxwell formulated a set of equations--Maxwell's field equations--that demonstrated that light should behave as a wave emitted by electromagnetic fields which would travel at a fixed velocity through space. This appeared to provide a way around Newton's relativity: by comparing one's own speed with the speed of light in one's vicinity, one should be able to measure one's absolute speed--or, what is practically the same, one's speed relative to a frame of reference that would be the same for all observers.

The assumption was whatever medium light was travelling through--whatever it was waves *of*--could be treated as a background against which to make other measurements. This inspired a search to determine the earth's velocity through this cosmic backdrop or "ether"--the "ether drift." The speed of light measured from the surface of the earth should appear to be greater when the earth was moving against the ether, slower when they were moving in the same direction. (Since the earth was hurtling through space *and* spinning, there should be at least some regularly changing measurements here.) A test made by Michelson and Morley toward the end of the century had the astonishing result that the speed of light appeared to be the same in every direction.

(To get a sense of how strange this was, imagine a car is driving down the highway. You want to see how fast it is going, so you and a bunch of friends get in cars and drive after it at different speeds. You talk on cell phones and each keep an eye on your speedometer and the other car. Some of you will get closer to the other car; some will fall further behind. When one of your friends--Bill--notices that he is neither gaining *nor* losing distance on the other car, you can judge that the strange car's speed is the same as Bill's. Michelson and Morley's result would be like you and all of your friends discovering that you are each neither gaining nor losing time on the strange car, even though you are all going different speeds.)

Einstein synthesized these various results in his 1905 paper "On the Electrodynamics of Moving Bodies."

Outline of the Theory

The fundamental idea in relativity is that we cannot talk of the physical quantities of velocity or acceleration without first defining a reference frame, and that a reference frame is defined by choosing particular matter as the basis for its definition. Thus all motion is defined and quantified relative to other matter. In the special theory of relativity it is assumed that reference frames can be extended indefinitely in all directions in space and time. The theory of special relativity concerns itself with inertial (non-accelerating) frames while general relativity deals with all frames of reference. In the general theory it is recognised that we can only define local frames to given accuracy for finite time periods and finite regions of space (similarly we can draw flat maps of regions of the surface of the earth but we cannot extend them to cover the whole surface without distortion). In general relativity Newton's laws are assumed to hold in local reference frames. In particular free particles travel in straight lines in local inertial (Lorentz) frames. When these lines are extended they do not appear straight, and are known as geodesics. Thus Newton's first law is replaced by the law of geodesic motion.

We distinguish inertial reference frames, in which bodies maintain a uniform state of motion unless acted upon by another body, from non-inertial frames in which freely moving bodies have an acceleration deriving from the reference frame itself. In non-inertial frames there is a perceived force which is accounted for by the acceleration of the frame, not by the direct influence of other matter. Thus we feel g-forces when cornering on the roads when we use a car as the physical base of our reference frame. Similarly there are coriolis and centrifugal forces when we define reference frames based on rotating matter (such as the Earth or a child's roundabout). The principle of equivalence in general relativity states that there is no local experiment to distinguish non-rotating free fall in a gravitational field from uniform motion in the absence of a gravitational field. In short there is no gravity in a reference frame in free fall. From this perspective the observed gravity at the surface of the Earth is the force observed in a reference frame defined from matter at the surface which is not free, but is acted on from below by the matter within the Earth, and is analogous to the g-forces felt in a car.

Mathematically, Einstein models space-time by a four-dimensional pseudo-Riemannian manifold, and his field equation states that the manifold's curvature at a point is directly related to the stress energy tensor at that point; the latter tensor being a measure of the density of matter and energy. Curvature tells matter how to move, and matter tells space how to curve.

The field equation is not uniquely proven, and there is room for other models, provided that they do not contradict observation. General relativity is distinguished from other theories of gravity by the simplicity of the coupling between matter and curvature, although we still await the unification of general relativity and quantum mechanics and the replacement of the field equation with a deeper quantum law. Few physicists doubt that such a theory of everything will give general relativity in the appropriate limit, just as general relativity predicts Newton's law of gravity in the non-relativistic limit.

Einstein's field equation contains a parameter called the "cosmological constant" › which was originally introduced by Einstein to allow for a static universe (ie one that is not expanding or contracting). This effort was unsuccessful for two reasons: the static universe described by this theory was unstable, and observations by Hubble a decade later confirmed that our universe is in fact not static but expanding. So › was abandoned, but quite recently, improved astronomical techniques have found that a non-zero value of › is needed to explain some observations.

The field equation reads as follows:

$$R_{ik} - \frac{g_{ik}R}{2} + \Lambda g_{ik} = 8\pi \frac{G}{c^4} T_{ik}$$

where R_{ik} is the Ricci curvature tensor, R is the Ricci curvature scalar, g_{ik} is the metric tensor, › is the cosmological constant, T_{ik} is the stress-energy tensor, À is pi, c is the speed of light and G is the gravitational constant which also occurs in Newton's law of gravity. g_{ik} describes the metric of the manifold and is a symmetric 4 x 4 tensor, so it has 10 independent components. Given the freedom of choice of the four spacetime coordinates, the independent equations reduce to 6.

The study of the solutions of this equation is one of the activities of a branch of astronomy named cosmology. It leads to the prediction of black holes and to the different models of evolution of the universe.

The vierbein formulation of general relativity

This is an alternative equivalent formulation of general relativity using four reference vector fields, called a *vierbein* or *tetrad*. We have four vector fields, e_a, a=0,1,2,3 such that $g(e_a,e_b)=\cdot_{ab}$ where

$$\eta = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}.$$

See sign convention. One thing to note is that we can perform an independent orthochronous, proper Lorentz transformation at each point (subject to smoothness, of course) and still get a valid tetrad. So, the tetrad formulation of GR is a gauge theory, but with a noncompact gauge group SO(3,1). It is also diffeomorphic invariant.

Suggested further reading

- Sean M. Carroll, introduction to general relativity, prerequisite knowledge includes linear algebra (matrices) and calculus
- Lewis Caroll Epstein: *Relativity Visualized.* Requires no mathematical background. Actually *explains* general relativity, rather than merely hinting at it with a few metaphors.
- Kip Thorne, Stephen Hawking: *Black Holes and Time Warps*, Papermac (1995). A recent popular account, by a leading expert.
- Misner, Thorne, Wheeler: *Gravitation*, Freeman (1973) ISBN 0716703440 . A classic graduate level text book, which, if somewhat long winded, pays more attention to the geometrical basis and the development of ideas in general relativity than some more modern approaches.
- Ray D'Inverno: *Introducing Einstein's Relativity*, Oxford University Press (1993). A modern undergraduate level text.
- Herman Bondi: *Relativity and Common Sense*, Heinemann (1964). A school level introduction to the principle of relativity by a renowned scientist.
- W. Perret and G.B. Jeffrey, trans.: *The Principle of Relativity: A Collection of Original Memoirs on the Special and General Theory of Relativity*, New York Dover (1923).
- MIT 8.962 Course Notes Notes and handouts from the MIT 8.962 course on General Relativity

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Quantum mechanics

Quantum mechanics, also referred to as **quantum physics**, is a physical theory that describes the behavior of matter at short length scales. It provides a quantitative explanation for two types of phenomena that classical mechanics and classical electrodynamics cannot account for:

- Some observable physical quantities, such as the total energy of a blackbody, take on discrete rather than continuous values. This phenomenon is called *quantization*, and the smallest possible intervals between the discrete values are called *quanta* (singular: *quantum*, from the Latin word for "quantity", hence the name "quantum mechanics.") The size of the quanta typically varies from system to system.
- Under certain experimental conditions, microscopic objects like atoms and electrons exhibit wave-like behavior, such as interference. Under other conditions, the same species of objects exhibit particle-like behavior ("particle" meaning an object that can be localized to a particular region of space), such as scattering. This phenomenon is known as wave-particle duality.

The foundations of quantum mechanics were established during the first half of the 20th century by the work of Niels Bohr, Werner Heisenberg, Erwin Schrödinger, Paul Dirac, and others. Some fundamental aspects of the theory are still being actively studied. Quantum mechanics has also been adopted as the underlying theory of many fields of physics and chemistry, including condensed matter physics, quantum chemistry, and particle physics.

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Description of the theory

Quantum mechanics describes the instantaneous state of a system with a *wave function* that encodes the probability distribution of all measurable properties, or *observables*. Possible observables for a system include energy, position, momentum, and angular momentum. Quantum mechanics does not assign definite values to the observables, instead making predictions about their probability distributions. The wavelike properties of matter are explained by the interference of wave functions.

Wave functions can change as time progresses. For example, a particle moving in empty space may be described by a wave function that is a wave packet centered around some mean position. As time progresses, the center of the wave packet changes, so that the particle becomes more likely to be located at a different position. The time evolution of wave functions is described by the Schrödinger equation.

Some wave functions describe probability distributions that are constant in time. Many systems that would be treated dynamically in classical mechanics are described by such static wave functions. For example, an electron in an unexcited atom is pictured classically as a particle circling the atomic nucleus, whereas in quantum mechanics it is described by a static, spherically symmetric probability cloud surrounding the nucleus.

When a measurement is performed on an observable of the system, the wavefunction turns into one of a set of wavefunctions that are called *eigenstates* of the observable. This process is known as wavefunction collapse. The relative probabilities of collapsing into each of the possible eigenstates is described by the instantaneous wavefunction just before the collapse. Consider the above example of a particle moving in empty space. If we measure the particle's position, we will obtain a random value x. In general, it is impossible for us to predict with certainty the value of x which we will obtain, although it is probable that we will obtain one that is near the center of the wave packet, where the amplitude of the wave function is large. After the measurement has been performed, the wavefunction of the particle collapses into one that is sharply concentrated around the observed position x.

During the process of wavefunction collapse, the wavefunction does not obey the Schrödinger equation. The Schrödinger equation is deterministic in the sense that, given a wavefunction at an initial time, it makes a definite prediction of what the wavefunction will be at any later time. During a measurement, the eigenstate to which the wavefunction collapses is probabilistic, not deterministic. The probabilistic nature of quantum mechanics thus stems from the act of measurement.

One of the consequences of wavefunction collapse is that certain pairs of observables, such as position and momentum, can never be simultaneously ascertained to arbitrary precision. This effect is known as Heisenberg's uncertainty principle.

Mathematical formulation

In the mathematically rigorous formulation developed by Paul Dirac and John von Neumann, the possible states of a quantum mechanical system are represented by unit vectors (called *state vectors*) residing in a complex separable Hilbert space (called the *state space*.) The exact nature of the Hilbert space is dependent on the system; for example, the

state space for position and momentum states is the space of square-integrable functions. The time evolution of a quantum state is described by the Schrödinger equation, in which the Hamiltonian, the operator corresponding to the total energy of the system, plays a central role.

Each observable is represented by a densely-defined Hermitian linear operator acting on the state space. Each eigenstate of an observable corresponds to an eigenvector of the operator, and the associated eigenvalue corresponds to the value of the observable in that eigenstate. If the operator's spectrum is discrete, the observable can only attain those discrete eigenvalues. During a measurement, the probability that a system collapses to each eigenstate is given by the absolute square of the inner product between the eigenstate vector and the state vector just before the measurement. We can therefore find the probability distribution of an observable in a given state by computing the spectral decomposition of the corresponding operator. Heisenberg's uncertainty principle is represented by the statement that the operators corresponding to certain observables do not commute.

The details of the mathematical formulation are contained in the article Mathematical formulation of quantum mechanics.

Interactions with other theories of physics

The fundamental rules of quantum mechanics are very broad. They state that the state space of a system is a Hilbert space and the observables are Hermitian operators acting on that space, but do not tell us which Hilbert space or which operators. These must be chosen appropriately in order to obtain a quantitative description of a quantum system. An important guide for making these choices is the correspondence principle, which states that the predictions of quantum mechanics reduce to those of classical (i.e. non-quantum) physics when a system becomes large, which is known as the *classical* or *correspondence limit*. One may therefore start from an established classical model of a particular system, and attempt to guess the underlying quantum model that gives rise to the classical model in the correspondence limit.

When quantum mechanics was originally formulated, it was applied to models whose correspondence limit was non-relativistic classical mechanics. For instance, the well-known model of the quantum harmonic oscillator uses an explicitly non-relativistic expression for the kinetic energy of the oscillator, and is thus a quantum version of the classical harmonic oscillator.

Early attempts to merge quantum mechanics with special relativity involved the replacement of the Schrödinger equation with a covariant equation such as the Klein-Gordon equation or the Dirac equation. While these theories were successful in explaining many experimental results, they had certain unsatisfactory qualities stemming from their neglect of the relativistic creation and annihilation of particles. A fully relativistic quantum theory required the development of quantum field theory, which applies quantization to a field rather than a fixed set of particles. The first complete quantum field theory, quantum electrodynamics, provides a fully relativistic description of the electromagnetic interaction.

The full apparatus of quantum field theory is often unnecessary for describing electrodynamic systems. A simpler approach, one employed since the inception of quantum mechanics, is to treat charged particles as quantum mechanical objects being acted on by a

classical electromagnetic field. For example, the elementary quantum model of the hydrogen atom describes the electric field of the hydrogen atom using a classical *1/r* Coulomb potential. This "semi-classical" approach fails if quantum fluctuations in the electromagnetic field play an important role, such as in the emission of photons by charged particles.

Quantum field theories for the strong nuclear force and the weak nuclear force have been developed. The quantum field theory of the strong nuclear force is quantum chromodynamics, which describes the interactions of the subnuclear particles, the quarks and gluons. The weak nuclear force and the electromagnetic force were unified, in their quantized forms, into a single quantum field theory known as electroweak theory.

It has proven difficult to construct quantum models of gravity, the remaining fundamental force. Semi-classical approximations are workable, and have led to predictions such as Hawking radiation. However, the formulation of a complete theory of quantum gravity is hindered by apparent incompatibilities between general relativity, the most accurate theory of gravity currently known, and some of the fundamental assumptions of quantum theory. The resolution of these incompatibilities is an area of active research.

Semi-classical approximations are techniques that make it possible to formulate a quantum problem with some physical quantities replaced by their classical analogues, in an effort to reduce the complexity of the model. Even within non-relativistic quantum mechanics, a fully microscopic treatment generally requires large-scale numerical computations. Analytic quantum solutions that describe the system behavior in terms of known mathematical functions are available only for a small class of systems, of which the harmonic oscillator and the hydrogen atom are the most important representatives.

Even the helium atom, containing just one more electron than hydrogen, defies all attempts at a fully analytic treatment in quantum mechanics. In such a situation, approximate semi-classical results can provide valuable insights. The necessary methods rely on a detailed understanding of the corresponding classical mechanics, allowing in particular for the existence of chaos. The study of these approximations belongs to the field of quantum chaos.

Applications

Much of modern technology operates under quantum mechanical principles. Examples include the laser, the electron microscope, and magnetic resonance imaging. Most of the calculations performed in computational chemistry rely on quantum mechanics.

Many of the phenomena studied in condensed matter physics are fully quantum mechanical, and cannot be satisfactorily modeled using classical physics. This includes the electronic properties of solids, such as superconductivity and semiconductivity. The study of semiconductors has led to the invention of the diode and the transistor, which are indispensable for modern electronics.

Researchers are currently seeking robust methods of directly manipulating quantum states. Efforts are being made to develop quantum cryptography, which will allow guaranteed secure transmission of information. A more distant goal is the development of quantum computers, which are expected to perform certain computational tasks with much greater efficiency than classical computers. Another active research topic is quantum

teleportation, which deals with techniques to transmit quantum states over arbitrary distances.

Philosophical debate

Since its inception, the many counter-intuitive results of quantum mechanics have provoked strong philosophical debate and many interpretations. See interpretation of quantum mechanics for more detail.

The Copenhagen interpretation, due largely to Niels Bohr, was the standard interpretation of quantum mechanics when it was first formulated. According to it, the probabilistic nature of quantum mechanics predictions cannot be explained in terms of some other deterministic theory, and do not simply reflect our limited knowledge. Quantum mechanics provides probabilistic results because the physical universe is itself probabilistic rather than deterministic.

Albert Einstein, himself one of the founders of quantum theory, disliked this loss of determinism in measurement. He held that quantum mechanics must be incomplete, and produced a series of objections to the theory. The most famous of these was the EPR paradox. John Stewart Bell's theoretical solution to the EPR paradox, and its later experimental verification, disproved a large class of such hidden variable theories and persuaded the majority of physicists that quantum mechanics is not an approximation to a nominally classical hidden-variable theory.

The many worlds interpretation, formulated in 1956, holds that all the possibilities described by quantum theory simultaneously occur in a "multiverse" composed of mostly independent parallel universes. While the multiverse is deterministic, we perceive non-deterministic behavior governed by probabilities because we can observe only the universe we inhabit.

The Bohm interpretation postulates the existence of a non-local, universal wavefunction (Schrödinger equation) which allows distant particles to interact instantaneously. It is not popular among physicists largely because it is considered very inelegant.

History

In 1900, Max Planck introduced the idea that energy is quantized, in order to derive a formula for the observed frequency dependence of the energy emitted by a black body. In 1905, Einstein explained the photoelectric effect by postulating that light energy comes in quanta called photons. In 1913, Bohr explained the spectral lines of the hydrogen atom, again by using quantization. In 1924, Louis de Broglie put forward his theory of matter waves.

These theories, though successful, were strictly phenomenological: there was no rigorous justification for quantization. They are collectively known as the *old quantum theory*.

The phrase "quantum physics" was first used in Johnston's *Planck's Universe in Light of Modern Physics*.

Modern quantum mechanics was born in 1925, when Heisenberg developed matrix mechanics and Schrödinger invented wave mechanics and the Schrödinger equation. Schrödinger subsequently showed that the two approaches were equivalent.

Heisenberg formulated his uncertainty principle in 1927, and the Copenhagen interpretation took shape at about the same time. In 1927, Paul Dirac unified quantum mechanics with special relativity. He also pioneered the use of operator theory, including the influential bra-ket notation. In 1932, John von Neumann formulated the rigorous mathematical basis for quantum mechanics as operator theory.

In the 1940s, quantum electrodynamics was developed by Feynman, Dyson, Schwinger, and Tomonaga. It served as a role model for subsequent quantum field theories.

The many worlds interpretation was formulated by Everett in 1956.

Quantum chromodynamics had a long history, beginning in the early 1960s. The theory as we know it today was formulated by Polizter, Gross and Wilzcek in 1975. Building on pioneering work by Schwinger, Higgs, Goldstone and others, Glashow, Weinberg and Salam independently showed how the weak nuclear force and quantum electrodynamics could be merged into a single electroweak force.

Recently, there has been much interest in quantum information.

Some quotations

I do not like it, and I am sorry I ever had anything to do with it.

Erwin Schrödinger, speaking of quantum mechanics

Those who are not shocked when they first come across quantum mechanics cannot possibly have understood it.

Niels Bohr

God does not play dice with the cosmos.

Albert Einstein

Einstein, don't tell God what to do.

Niels Bohr in response to Einstein

I think it is safe to say that no one understands quantum mechanics.

Richard Feynman

It's always fun to learn something new about quantum mechanics.

Benjamin Schumacher

If that turns out to be true, I'll quit physics.

Max von Laue, Nobel Laureate 1914, of de Broglie's thesis on electrons having wave properties.

Anyone wanting to discuss a quantum mechanical problem had better understand and learn to apply quantum mechanics to that problem.

Willis Lamb, Nobel Laureate 1955

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Quantum field theory

Quantum field theory (QFT) is the application of quantum mechanics to fields. It provides a theoretical framework widely used in particle physics and condensed matter physics. In particular, the quantum theory of the electromagnetic field, known as quantum

electrodynamics, is one of the most well-tested and successful theories in physics. The fundamentals of quantum field theory were developed between the late 1920s and the 1950s, notably by Dirac, Pauli, Tomonaga, Schwinger, Feynman, and Dyson.

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Shortcomings of ordinary quantum mechanics

Quantum field theory corrects several deficiencies of ordinary quantum mechanics, which we will briefly discuss. The Schrödinger equation, in its most commonly-encountered form, is

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\Psi(\mathbf{r},t) = i\hbar\frac{\partial\Psi}{\partial t}(\mathbf{r},t)$$

where ¨ is the wavefunction of a particle, *m* its mass, and *V* an applied potential energy.

There are two problems with this equation. Firstly, it is not relativistic, reducing to classical mechanics rather than relativistic mechanics in the correspondence limit. To see this, we note that the first term on the left is only the classical kinetic energy $p^2/2m$, with the rest energy mc^2 omitted. It is possible to modify the Schrödinger equation to include the rest energy, resulting in the Klein-Gordon equation or the Dirac equation. However, these equations have many unsatisfactory qualities; for instance, they possess energy spectra which extend to -, so that there is no ground state. Such inconsistencies occur because these equations neglect the possibility of dynamically creating or destroying particles, which is a crucial aspect of relativity. Einstein's famous mass-energy relation predicts that sufficiently massive particles can decay into several lighter particles, and sufficiently energetic particles can combine to form massive particles. For example, an electron and a positron can annihilate each other to create photons. Such processes must be accounted for in a truly relativistic quantum theory.

The second problem occurs when we seek to extend the equation to large numbers of particles. It was discovered that quantum mechanical particles of the same species are indistinguishable, in the sense that the wavefunction of the entire system must be symmetric (bosons) or antisymmetric (fermions) when the coordinates of its constituent particles are exchanged. This makes the wavefunction of systems of many particles extremely complicated. For example, the general wavefunction of a system of *N* bosons is written as

$$\Phi(r_1, ..., r_N) = \frac{1}{\sqrt{N!}}\sum_p \phi_{p(1)}(r_1)\cdots\phi_{p(N)}(r_N)$$

where r_i are the coordinates of the *i*-th particle, *Æi* are the single-particle wavefunctions, and the sum is taken over all possible permutations of *p* elements. In general, this is a sum of *N!* (*N* factorial) distinct terms, which quickly becomes unmanageable as *N* increases.

Quantum fields

Both of the above problems are resolved by moving our attention from a set of indestructible particles to a *quantum field*. The procedure by which quantum fields are constructed from individual particles was introduced by Dirac, and is (for historical reasons) known as second quantization.

We should mention two possible points of confusion. Firstly, the aforementioned "field" and "particle" descriptions do *not* refer to wave-particle duality. By "particle", we refer to entities which possess both wave and point-particle properties in the usual quantum mechanical sense; for example, these "particles" are generally not located at a fixed point, but have a certain probability of being found at each position in space. What we refer to as a "field" is an entity existing at every point in space, *which regulates the creation and annihilation of the particles*. Secondly, quantum field theory is essentially quantum mechanics, and not a replacement for quantum mechanics. Like any quantum system, a quantum field possesses a Hamiltonian *H* (albeit one that is more complicated than typical single-particle Hamiltonians), and obeys the usual Schrödinger equation

$$H\left|\psi(t)\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle$$

(Quantum field theory is often formulated in terms of a Lagrangian, which is more convenient to work with. However, the Lagrangian and Hamiltonian formulations are believed to be equivalent.)

In second quantization, we make use of particle indistinguishability by specifying multi-particle wavefunctions in terms of single-particle *occupation numbers*. For example, suppose we have a system of *N* bosons which can occupy various single-particle states Æ1, Æ2, Æ3, and so on. The usual method of writing a multi-particle wavefunction is to assign a state to each particle and then impose exchange symmetry. As we have seen, the resulting wavefunction is an unwieldy sum of *N!* terms. In the second quantized approach, we simply list the number of particles in each of the single-particle states, with the understanding that the multi-particle wavefunction is symmetric. To be precise, suppose that *N = 3*, with one particle in state Æ1 and two in state Æ2. The normal way of writing the wavefunction is

$$\frac{1}{\sqrt{3}}\left[\phi_1(r_1)\phi_2(r_2)\phi_2(r_3) + \phi_2(r_1)\phi_1(r_2)\phi_2(r_3) + \phi_2(r_1)\phi_2(r_2)\phi_1(r_3)\right]$$

whereas in second quantized form it is simply

$$|1, 2, 0, 0, \cdots\rangle$$

Though the difference is entirely notational, the latter form makes it extremely easy to *define* **creation** and **annihilation operators**, which add and subtract particles from multi-particle states. These creation and annihilation operators are very similar to those defined for the quantum harmonic oscillator, which added and subtracted energy quanta. However,

these operators literally create and annihilate particles with a given quantum state. For example, the annihilation operator a_2 has the following effects:

$$a_2|1,2,0,0,\cdots\rangle \equiv |1,1,0,0,\cdots\rangle\sqrt{2}$$

$$a_2|1,1,0,0,\cdots\rangle \equiv |1,0,0,0,\cdots\rangle$$

$$a_2|1,0,0,0,\cdots\rangle \equiv \quad 0$$

(The 2 factor in the first line normalizes the wavefunction, and is not important.)

Finally, we introduce *field operators* that define the probability of creating or destroying a particle at a particular point in space. It turns out that single-particle wavefunction are usually enumerated in terms of their momenta (as in the particle in a box problem), so field operators can be constructed by applying the Fourier transform to the creation and annihilation operators. For example, the bosonic field annihilation operator Æ(r) (which is not to be confused with the wavefunction) is

$$\phi(\mathbf{r}) \equiv \sum_i e^{i\mathbf{k}_i\cdot\mathbf{r}} a_i$$

In quantum field theories, Hamiltonians are written in terms of either the creation and annihilation operators or, equivalently, the field operators. The former practice is more common in condensed matter physics, whereas the latter is more common in particle physics since it makes it easier to deal with relativity. An example of a Hamiltonian written in terms of creation and annihilation operators is

$$H = \sum_k E_k\, a_k^\dagger\, a_k$$

This describes a field of free (non-interacting) bosons, where E_k is the kinetic energy of the k-th momentum mode. In fact, this Hamiltonian is useful for describing non-interacting phonons.

Wightman axioms

This is one of the many attempts to put quantum field theory on a firm mathematical footing.

Suggested reading

Peskin, M. and D. Schroeder. 1995. An Introduction to quantum field theory.
Weinberg, Steven. The Quantum theory of fields. vol.

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Standard Model

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Standard Model

The **Standard Model** of particle physics is a theory which describes the strong, weak, and electromagnetic fundamental forces, as well as the fundamental particles that make up all matter. It is a quantum field theory, and consistent with both quantum mechanics and special relativity. To date, almost all experimental tests of the three forces described by the Standard Model have agreed with its predictions. However, the Standard Model is not a complete theory of fundamental interactions, primarily because it does not describe gravity.

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Content of the Standard Model

The Standard Model contains both fermionic and bosonic fundamental particles. Fermions are particles which possess half-integer spin and obey the Pauli exclusion principle, which states that no fermions can share the same quantum state. Bosons possess integer spin and do not obey the Pauli exclusion principle. Informally speaking, fermions are particles of matter and bosons are particles that transmit forces. For a detailed description of the differences between fermions and bosons, see the article on identical particles.

In the Standard Model, the theory of the electroweak interaction (which describes the weak and electromagnetic interactions) is combined with the theory of quantum chromodynamics. Each of these theories are gauge field theories, meaning that they model the forces between fermions by coupling them to bosons which mediate (or "carry") the forces. The Lagrangean of each set of mediating bosons is invariant under a transformation called a gauge transformation, so these mediating bosons are referred to as *gauge bosons*. The bosons in the Standard Model are:

- Photons, which mediate the electromagnetic interaction.

- W^+ and W^- and Z^0 bosons, which mediate the weak nuclear force
- Eight species of gluons, which mediate the strong nuclear force. Six of these gluons are labelled as pairs of "colors" and "anti-colors" (for example, a gluon can carry "red" and "anti-green".) The other two species are a more complicated mix of colors and anti-colors.
- The Higgs bosons, which induce spontaneous symmetry breaking of the gauge groups and are responsible for the existence of inertial mass.

It turns out that the gauge transformations of the gauge bosons can be exactly described using a unitary group called a "gauge group". The gauge group of the strong interaction is SU(3), and the gauge group of the electroweak interaction is SU(2)×U(1). Therefore, the Standard Model is often referred to as SU(3)×SU(2)×U(1). The Higgs boson is the only boson in the theory which is not a gauge boson; it has a special status in the theory, and has been the subject of some controversy. Gravitons, the bosons believed to mediate the gravitational interaction, are not accounted for in the Standard Model.

There are twelve different types, or "flavours", of fermions in the Standard Model. Amongst the proton, neutron, and electron, those fermions which constituent the vast majority of matter, the Standard Model considers only the electron a fundamental particle. The proton and neutron are aggregates of smaller particles known as quarks, which are held together by the strong interaction. The fundamental fermions in the Standard Model are:

Left handed fermions in the Standard Model

Fermion	Symbol	Electromagnetic charge	Weak charge (as a representation)*	Weak isospin	Hypercharge	Strong charge (color) (as a representation)*	Mass**
		Generation 1					
Left Handed Electron	e	-1	2	-1/2	-1/2	1	0.511 MeV
Left Handed Electron neutrino	½e	0	2	+1/2	-1/2	1	< 50 eV
Left Handed Positron	e^c	1	1	0	1	1	0.511 MeV
Left Handed Electron antineutrino	ν_e^c	0	1	0	0	1	< 50 eV
Left Handed Up quark	u	+2/3	2	+1/2	+1/6	3	~5 MeV ***
Left Handed Down quark	d	-1/3	2	-1/2	+1/6	3	~10 MeV ***
Left Handed antiUp antiquark	u^c	-2/3	1	0	-2/3	$\bar{3}$	~5 MeV ***
Left Handed antiDown antiquark	d^c	+1/3	1	0	+1/3	$\bar{3}$	~10 MeV ***
		Generation 2					

Left Handed Muon	¼	-1	2	-1/2	-1/2	1	105.6 MeV
Left Handed Muon neutrino	½¼	0	2	+1/2	-1/2	1	< 0.5 MeV
Left Handed antiMuon	¼^c	1	1	0	1	1	105.6 MeV
Left Handed Muon antineutrino	ν_μ^c	0	1	0	0	1	< 0.5 MeV
Left Handed Charm quark	*c*	+2/3	2	+1/2	+1/6	3	~1.5 GeV
Left Handed Strange quark	*s*	-1/3	2	-1/2	+1/6	3	~100 MeV
Left Handed antiCharm antiquark	c^c	-2/3	1	0	-2/3	$\bar{3}$	~1.5 GeV
Left Handed antiStrange antiquark	s^c	+1/3	1	0	+1/3	$\bar{3}$	~100 MeV
Generation 3							
Left Handed Tau	Ä	-1	2	-1/2	-1/2	1	1.784 GeV
Left Handed Tau neutrino	½Ä	0	2	+1/2	-1/2	1	< 70 MeV
Left Handed antiTau	Ä^c	1	1	0	1	1	1.784 GeV
Left Handed Tau antineutrino	ν_τ^c	0	1	0	0	1	< 70 MeV
Left Handed Top quark	*t*	+2/3	2	+1/2	+1/6	3	178 GeV
Left Handed Bottom quark	*b*	-1/3	2	-1/2	+1/6	3	~4.7 GeV
Left Handed antiTop antiquark	t^c	-2/3	1	0	-2/3	$\bar{3}$	178 GeV
Left Handed antiBottom antiquark	b^c	+1/3	1	0	+1/3	$\bar{3}$	~4.7 GeV

* - These are not ordinary Abelian charges which can be added together but labels of Group representations of Lie groups.

** - Mass is really a coupling between a left handed fermion and a right handed fermion. For example, the mass of an electron is really a coupling between a left handed electron and a right handed electron, which is the antiparticle of a left handed positron. Also neutrinos show large mixings in their mass coupling, so it's not accurate to talk about neutrino masses in the flavor basis or to suggest a left handed electron neutrino and a right handed electron neutrino have the same mass as this table seems to suggest.

*** - What is actually measured experimentally are the masses of baryons and hadrons and various cross section rates. Since quarks can't be isolated because of QCD confinement, the quantity here is supposed to be the mass of the quark at the renormalization scale of the QCD phase transition. In order to compute this quantity, physicists have to set up a lattice model and try out various masses for the quarks until the model comes up with a close fit with experimental data. Since the masses of the first generation quarks are significantly below the QCD scale, the uncertainties here are pretty large. In fact, current QCD lattice models seem to suggest a significantly lower mass of these quarks from that of this table.

The fermions can be arranged in three "generations", the first one consisting of the electron, the up and down quarks, and the electron neutrino. All ordinary matter is made from first generation particles; the higher generation particles decay quickly into the first generation ones and can only be generated for a short time in high-energy experiments. The reason for arranging them in generations is that the four fermions in each generation behave almost exactly like their counterparts in the other generations; the only difference is in their masses. For example, the electron and the muon both have half-integer spin and unit electric charge, but the muon is about 200 times more massive.

The electron and the electron-neutrino, and their counterparts in the other generations, are called "leptons". Unlike the other fermions, they do not possess a quality called "color", and therefore their interactions (weak and electromagnetic) fall off rapidly with distance. On the other hand, the strong force between quarks gets stronger with distance, so that quarks are always found in colorless combinations called hadrons. These are either fermionic baryons composed of three quarks (the proton and neutron being the most familiar example) or bosonic mesons composed of a quark-antiquark pair (such as pions). The mass of such aggregates exceeds that of the components due to their binding energy.

Tests and predictions

The Standard Model predicted the existence of W and Z bosons, the gluon, the top quark and the charm quark before these particles had been observed. Their predicted properties were experimentally confirmed with good precision.

The Large Electron-Positron collider at CERN tested various predictions about the decay of Z bosons, and found them confirmed.

Challenges to the Standard Model

Although the Standard Model has had great success in explaining experimental results, it has never been accepted as a complete theory of fundamental physics. This is because it has two important defects:

1. The model contains 19 free parameters, such as particle masses, which must be determined experimentally (plus another 10 for neutrino masses). These parameters cannot be independently calculated.
2. The model does not describe the gravitational interaction.

Since the completion of the Standard Model, many efforts have been made to address both problems.

One attempt to address the first defect is known as grand unification. The so-called grand unified theories (GUTs) hypothesized that the SU(3), SU(2), and U(1) groups are actually subgroups of a single large symmetry group. At high energies (far beyond the reach of current experiments), the symmetry of the unifying group is preserved; at low energies, it reduces to SU(3)×SU(2)×U(1) by a process known as spontaneous symmetry breaking. The first theory of this kind was proposed in 1974 by Georgi and Glashow, using SU(5) as the unifying group. A distinguishing characteristic of these GUTs is that, unlike the Standard model, they predict the existence of proton decay. In 1999, the Super-Kamiokande neutrino observatory reported that it had not detected proton decay, establishing a lower limit on the proton half-life of 6.7×10^{32} years. This and other experiments have falsified numerous GUTs, including SU(5).

In addition, there are cosmological reasons why the standard model is believed to be incomplete. Within it, matter and antimatter are symmetric. While the preponderance of matter in the universe can be explained by saying that the universe just started out this way, this explanation strikes most physicists as inelegant. Furthermore, the Standard Model provides no mechanism to generate the cosmic inflation that is believed to have occurred at the beginning of the universe, a consequence of its omission of gravity.

The Higgs boson, which is predicted by the Standard Model, has not been observed as of 2002.

The first experimental deviation from the Standard Model came in 1998, when Super-Kamiokande published results indicating neutrino oscillation. This implied the existence of non-zero neutrino masses since massless particles travel at the speed of light and so do not experience the passage of time.

The Standard Model did not accommodate massive neutrinos, because it assumed the existence of only "left-handed" neutrinos, which have spin aligned counter-clockwise to their axis of motion. If neutrinos have non-zero mass, they necessarily travel slower than the speed of light. Therefore, it would be possible to "overtake" a neutrino, choosing a reference frame in which its direction of motion is reversed without affecting its spin (making it right-handed).

Since then, physicists have revised the Standard Model to allow neutrinos to have mass, which make up additional free parameters beyond the initial 19. Confusingly, this new model is still called by the same name as the old one; the Standard Model.

A further extension of the Standard Model can be found in the theory of supersymmetry, which proposes a massive supersymmetric "partner" for every particle in the conventional Standard Model. Supersymmetric particles have been suggested as a candidate for explaining dark matter.

Further Reading

- Y. Hayato *et al.*, *Search for Proton Decay through p ' ½K+ in a Large Water Cherenkov Detector*. Phys. Rev. Lett. **83**, 1529 (1999).

See also: Theory of everything

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Fluid mechanics

Fluid mechanics is a branch of physics that describes the behavior of fluids (which include liquids and gases). Fluid mechanics is often considered a branch of continuum mechanics, because fluids are often treated as continuous material, describable with differential equations and tensors.

The central equations for fluid mechanics are the Navier-Stokes equations, which are non-linear differential equations that describe fluid flow. These equations are derivable from conservation of mass and conservation of momentum.

Fluid mechanics is related to statistical mechanics, because fluids can also be modelled as a statistically large number of particles.

The concept of a fluid is surprisingly general. For example, some of the basic mathematics in traffic engineering is derived from considering traffic as a continuous fluid.

See also

- acoustic theory largely derives from fluid mechanics.

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Proposed theories

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Theory of everything

In physics, a **theory of everything (TOE)** is a theory that unifies the four fundamental forces of nature: gravity, the strong nuclear force, the weak nuclear force, and the electromagnetic force, and is the goal of researchers in quantum gravity. A TOE is sometimes called a **supergrand unified theory**.

A theory of everything is needed to explain phenomena such as the big bang or gravitational singularities in which the current theories of general relativity and quantum mechanics break down. Theoretical motivations for finding a theory of everything include the Platonic belief that the ultimate nature of the universe is simple and therefore the current models of the universe such as the standard model cannot be complete because they are too complicated.

There have been numerous theories of everything proposed by theoretical physicists over the last century, but as yet none has been able to stand up to experimental scrutiny or there is tremendous difficulty in getting the theories to produce even experimentally testable results. The primary problem in producing a theory of everything is that quantum mechanics and general relativity have radicially different descriptions of the universe, and the obvious ways of combining the two lead quickly to the renormalization problem in which the theory does not give finite results for experimentally testable quantities.

Popular candidates for a theory of everything at the moment include loop quantum gravity, string theory, and M-theory. Most of these theories attempt to deal with the renormalization problem by setting up some lower bound on the length scales possible. Also, early 21st century theories of everything tend to suppose that the universe actually has more dimensions than the easily observed three of space and one of time. The motivation behind this approach began with the Kaluza-Klein theory in which it was noted that adding one dimension to general relativity would produce the electromagnetic Maxwell's equations. This has led to efforts to work with theories with large number of dimensions in the hopes that this would produce equations which are similar to known laws of physics.

In the late 1990's, it was noted that one problem with several of the candidates for theories of everything was that they did not predict constrain the characteristics of the predicted universe. For example, many theories of quantum gravity can create universes with arbitrary numbers of dimensions or with arbitrary cosmological constants. One bit of speculation is that there many indeed be a huge number of universes, but that only a small number of them are habitable, and hence the fundamental constants of the universe are ultimately the result of the anthropic principle rather than a consequence of the theory of everything.

There is also a philosophical debate within the physics community as to whether or not a theory of everything should be seen as the fundamental law of the universe. One view is the hard reductionist view that the TOE is the fundamental law of the universe and that all other theories of the universe are a consequence of the TOE. Another view, is that there are laws which Steven Weinberg calls **free floating laws** which govern the behavior of complex systems, and while these laws are related to the theory of everything, they cannot been seen as less fundamental than the TOE.

Theories of everything must be distinguished from grand unified theories (or GUTs), which attempt to unite all the fundamental forces except gravity. A unified field theory that unites the electromagnetic and weak nuclear forces into a single electroweak force has already been established; GUTs attempt to unify the strong nuclear and electroweak forces.

Speculative ideas

Many alternative thinkers have attempted to create "theories of everything".

Attempts to create theories of everything are common among people outside the professional physics community. Unfortunately some of these theories suffer from the inability to make quantifiable and/or falsifible predictions. Unlike professional physicists, who are generally aware that their proposed theory is incomplete, untested, and possibly wrong, amateurs who create TOE's tend to be unaware of the need and mechanisms for testing scientific theories and the fact that most proposed theories (logically, all but one) are wrong.

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Grand unification theory

Grand unification, **Grand unified theory** or **GUT** (a misnomer, really) refers to a theory in physics that unifies the strong interaction and electroweak interaction. Several such theories have been proposed, but none is currently universally accepted. The (future) theory that will also include gravity is termed theory of everything.

GUTs also predict the existence of topological defects such as monopoles, cosmic strings, domain walls, and others. None have been observed and their absence is known as the monopole problem in cosmology.

Some common GUT groups are:

- SU(5), Georgi-Glashow model
- SO(10)
- SU(5)XU(1), Flipped SU(5).
- SU(4)XSU(2)XSU(2), Pati-Salam model
- SU(3)XSU(3)XSU(3), Trinification
- E_6
- Technicolor models

Note that it is meant that these groups are Lie algebras. The Lie group could be $[SU(4) \times SU(2) \times SU(2)]/\mathbb{Z}_2$, just to take a random example.

As of 2003, there is still no hard evidence nature is described by a GUT theory. In fact, since the Higgs particle hasn't been discovered yet, it's not even certain if the Standard Model is fully accurate.

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M-theory

M-theory is the unknown theory of everything which would combine all five superstring theories and 11-dimensional supergravity together. According to Dr. Edward Witten, who proposed the theory, mathematical tools which have yet to be invented are needed in order to fully understand it.

The following article is somewhat technical in nature; see M-theory simplified for a less technical article.

M-theory's relation to superstrings and supergravity

M-Theory in various geometric backgrounds is associated with the different superstring theories (in different geometric backgrounds), and these limits are related to each other by the principle of duality. Two physical theories are dual to each other if they have identical physics after a certain mathematical transformation.

Type IIA and IIB are related by T-duality, as are the two Heterotic theories. Type I and Heterotic SO(32) are related by the S-duality. Type IIB is also S-dual with itself.

- The **type II** theories have two supersymmetries in the ten-dimensional sense, the rest just one.
- The **type I** theory is special in that it is based on unoriented open and closed strings.
- The other four are based on oriented closed strings.
- The **IIA** theory is special because it is non-chiral (parity conserving).
- The other four are chiral (parity violating).

In each of these cases there is an 11th dimension that becomes large at *strong coupling*. In the **IIA** case the 11th dimension is a circle. In the **HE** case it is a line interval, which makes eleven-dimensional space-time display two ten-dimensional boundaries. The strong coupling limit of either theory produces an 11-dimensional space-time. This eleven-dimensional description of the underlying theory is called **"M- theory"**. A string's space-time history can be viewed mathematically by functions like

X¼(Ã,Ä)

that describe how the string's two-dimensional sheet coordinates **(Ã,Ä)** map into space-time **X¼**

One interpretation of this result is that the 11th dimension was always present but invisible because the radius of the 11th dimension is proportional to the string coupling

contant and the traditional perturbative string theory presumes it to be infinitesimal. Another interpretation is that dimension is not a fundamental concept of M-theory at all.

Characteristics of M-theory

M-theory contains much more than just strings. It contains both higher and lower dimensional objects. These objects are called p-branes where p denotes their dimensionality (thus, 1-brane for a string and 2-brane for a membrane). Higher dimensional objects were always present in superstring theory but could never be studied before the Second Superstring Revolution because of their non-perturbative nature.

Insights into non-perturbative properties of p-branes stem from a special class of p-branes called Dirichlet p-branes (Dp-branes). This name results from the boundary conditions assigned to the ends of open strings in type I superstrings.

Open strings of the type I theory can have endpoints which satisfy the Neumann boundary condition. Under this condition, the endpoints of strings are free to move about but no momentum can flow into or out of the end of a string. The T duality infers the existence of open strings with positions fixed in the dimensions that are T-transformed. Generally, in type II theories, we can imagine open strings with specific positions for the end-points in some of the dimensions. This lends an inference that they must end on a preferred surface. Superficially, this notion seems to break the *relativistic invariance* of the theory, possibly paradoxical. The resolution of this paradox is that strings end on a p-dimensional dynamic object, the Dp-brane.

The importance of D-branes stems from the fact that they make it possible to study the excitations of the brane using the renormalizable 2D quantum field theory of the open string instead of the non-renormalizable world-volume theory of the D-brane itself. In this way it becomes possible to compute non-perturbative phenomena using perturbative methods. Many of the previously identified p-branes are D-branes ! Others are related to D-branes by duality symmetries, so that they can also be brought under mathematical control. D-branes have found many useful applications, the most remarkable being the study of black holes. *Strominger and Vafa have shown that D-brane techniques can be used to count the quantum microstates associated to classical black hole configurations.* The simplest case first explored was **static extremal charged black holes** in five dimensions. Strominger and Vafa proved for large values of the charges the entropy **S = log N,** where N is equal to the number of quantum states that system can be in, agrees with the **Bekenstein-Hawking** prediction (1/4 the area of the event horizon).

This result has been generalized to black holes in 4D as well as to ones that are near extremal (and radiate correctly) or rotating, a remarkable advance. It has not yet been proven that there is any problematic breakdown of quantum mechanics due to black holes.

Further Reading:

- Michael J. Duff, *The Theory Formerly Known as Strings*, Scientific American, February 1998
- John Gribbin, *The Search for Superstrings, Symmetry, and the Theory of Everything*, ISBN 0316329754 , Little, Brown & Company, 1ST BACK B Edition, August 2000, specifically pages 177-180.

• Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*, ISBN 0393046885 , W.W. Norton & Company, February 1999

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Loop quantum gravity

Loop quantum gravity (LQG) is a proposed quantum theory of spacetime which blends together the seemingly incompatible theories (see below) of quantum mechanics and general relativity. As a theory of quantum gravity, it is the main competitor of string theory, although *stringy* people outnumber *loopy* people by a factor of roughly 10:1. The main successes of Loop Quantum Gravity are: a nonperturbative quantization of 3-space geometry, with quantized area and volume operators; a calculation of the entropy of physical black holes; and a proof by example that it is not necessary to have a theory of everything in order to have a sensible candidate for a quantum theory of gravity. Its main shortcomings are: not yet having a picture of dynamics but only of kinematics; not yet able to incorporate particle physics; not yet able to recover the classical limit.

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The incompatibility between quantum mechanics and general relativity

The fundamental lesson of general relativity is that there is no fixed spacetime background, as found in Newtonian mechanics and special relativity. While easy to grasp in principle, this is the hardest idea to understand about General Relativity, and its consequences are profound and not fully understood, even at the classical level. To a certain extent, general relativity can be seen to be a completely relational theory, in which the only physically relevant information is the relationship between different events in space-time.

On the other hand, quantum mechanics since its invention has depended on a fixed background (non-dynamical) structure. In the case of quantum mechanics, it is time that is

given and not dynamical, just as in Newtonian classical mechanics. In relativistic quantum field theory, just as in classical field theory, Minkowski spacetime is the fixed background of the theory. Finally, string theory started out as a generalization of quantum field theory where instead of point particles, string-like objects propagate in a fixed spacetime background. No attempt will be made to describe string theory/M-theory in more depth in this article, since it wouldn't be possible to do it justice.

Quantum field theory on curved (non-Minkowskian) backgrounds, while not a quantum theory of gravity, has shown that some of the core assumptions of quantum field theory cannot be carried over to curved spacetime, let alone to full-blown quantum gravity. In particular, the vacuum, when it exists, is shown to depend on the path of the observer though space-time. Also, the field concept is seen to be fundamental over the particle concept (which arises as a convenient way to describe localized interactions).

Historically, there have been two reactions to the apparent inconsistency of quantum theories with the necessary background-independence of general relativity. The first is that the geometric interpretation of General relativity is not fundamental, but just an emergent quality of some background-dependent theory. This is explicitly stated, for example, in Steven Weinberg's classic *Gravitation and Cosmology* textbook. The opposing view is that background-independence is fundamental, and quantum mechanics needs to be generalized to settings where there is no a-priori specified time. The geometric point of view is expounded in the classic text *Gravitation*, by Misner, Wheeler and Thorne. It is interesting that two books by giants of theoretical physics expressing completely opposite views of the meaning of gravitation were published almost simultaneously in the early 1970's. The reason was that an impasse had been reached. Since then, though, progress was rapid on both fronts, leading ultimately to String Theory and Loop Quantum Gravity.

Loop quantum gravity is the fruit of the effort to formulate a background-independent quantum theory. Topological quantum field theory provided an example of background-independent quantum theory, but with no local degrees of freedom, and only finitely many degrees of freedom globally. This is inadequate to describe gravity, which even in vacuum has local degrees of freedom according to general relativity.

Wilson loops and spin networks

In LQG, the fabric of spacetime is a foamy network of interacting loops mathematically described by spin networks. These loops are about 10^{-35} meters in size, called the Planck scale. The loops knot together forming edges, surfaces, and vertices, much as do soap bubbles joined together. In other words, spacetime itself is quantized. Any attempt to divide a loop would, if successful, cause it to divide into two loops each with the original size. In LQG, spin networks represent the quantum states of the geometry of relative spacetime. Looked at another way, Einstein's theory of general relativity is (as Einstein predicted) a classical approximation of a quantized geometry.

LQG and quantum cosmology

An important principle in quantum cosmology that LQG adheres to is that there are no observers outside the universe. All observers must be a part of the universe they are observing. However, because light cones limit the information that is available to any observer, the Platonic idea of absolute truths does not exist in a LQG universe. Instead, there exists a consistency of truths in that every observer will report consistent (not necessarily the same) results if truthful.

Another important principle is the issue of the cosmological constant, which is the energy density inherent in a vaccuum. Because string theory/m-theory makes use of supersymmetry, the physics implies a negative or a zero comsological constant. This is in apparent contradiction to observation, which observes a positive, but very close to zero, cosmological constant. However, the ground state in LQG is positive, although very small; LQG, unlike its rival string theory/m-theory, apparently incorporates a positive cosmological constant in agreement with observation.

Experimental tests of LQG?

Unlike string theory and M-theory, LQG makes experimentally testable hypotheses.

The path taken by a photon through a discrete spacetime geometry would be different from the path taken by the same photon through continuous spacetime. Normally, such differences should be insignificant, but Giovanni Amelino-Camelia points out that photons which have travelled from distant galaxies may reveal the structure of spacetime. LQG predicts that more energetic photons should travel ever so slightly faster than less energetic photons. This effect would be too small to observe within our galaxy. However, light reaching us from gamma ray bursts in other galaxies should manifest a varying spectral shift over time. In other words, distant gamma ray bursts should appear to start off more bluish and end more reddish. LQG physcists anxiously await results from space-based gamma-ray spectrometry experiments -- a mission set to launch in September, 2006.

The recent result that gravity propagates at the speed of light is consistent with LQG. However, the result significantly constrains string theory and probably M-theory because large numbers of dimensions would allow gravity to propagate along extra dimensions. This result does not by itself rule out all forms of string theory.

People in LQG and related areas

Loop quantum gravity theorists:

- Abhay Ashtekar
- John Baez
- Julian Barbour
- Louis Crane
- Laurent Freidel
- Rodolfo Gambini
- Christopher Isham

- Fotini Markopoulou-Kalamara
- Carlo Rovelli
- Lee Smolin
- Thomas Thiemann

Bibliography

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  - Lee Smolin, *Three Roads to Quantum Gravity*
- Introductory/expository works:
  - John Baez and Javier Perez de Muniain, *Gauge Fields, Knots and Quantum Gravity*, World Scientific (1994), ISBN 9810220340
  - Carlo Rovelli, *A Dialog on Quantum Gravity*, preprint available as hep-th/0310077
- Advanced books, reports, conference proceedings:
  - Robert M. Wald, *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*, Chicago University Press (1994), ISBN 0226-87027-8
  - Robert M. Wald, *General Relativity*, Chicago University Press, ISBN 0-226-87033-2
  - Steven Weinberg, *Gravitation and Cosmology: principles and applications of the general theory of relativity*, Wiley (1972), ISBN 0-471-92567-5
  - Misner, Thorne and Wheeler, *Gravitation*, Freeman, (1973), ISBN 0-7167-0344-0
  - A. Ashtekar, *Lectures on Non-Perturbative Canonical Gravity*, World Scientific (1991)
  - Rodolfo Gambini and Jorge Pullin, *Loops, Knots, Gauge Theories and Quantum Gravity*
  - John Baez (ed.), *Knots and Quantum Gravity*

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Emergence

Emergence is the process of deriving some new and coherent structures, patterns and properties in a complex system. Emergent phenomena occur due to the pattern of interactions between the elements of a system over time. Emergent phenomena are often unexpected, nontrivial results of relatively simple interactions of relatively simple components. What distinguishes a complex system from a merely complicated one is that some behaviours and patterns emerge in complex systems as a result of the patterns of relationship between the elements.

An **emergent behaviour** is shown when a number of simple entities (agents) operate in an environment, forming more complex behaviours as a collective. The complex behaviour is not a property of any single such entity, nor can it easily be predicted or deduced from behaviour in the lower-level entities. The shape and behaviour of a flock of birds or school of fish are readily understandable examples, and it is typical that the mechanisms governing the flock or school are harder to grasp than the behaviour of individual birds or fish.

Emergent processes or behaviours can be seen in a lot of places, from any multicellular biological organism to traffic patterns or organizational phenomena to computer simulations. The stock market is an example of emergence on a grand scale. As a whole it precisely regulates the relative prices of companies across the world, yet it has no leader; there is no one entity which controls the workings of the entire market. Each agent, or investor, has knowledge of only a limited number of companies within their portfolio, and must follow the regulatory rules of the market. Through the interactions of individual investors the complexity of the stock market as a whole emerges.

The study of emergent behaviours is not generally considered a homogeneous field, but divided across its application or problem domains.

Not to be confused with emergency.

Bibliography

- Stephen Johnson, *Emergence* (2002)
- Stephen Wolfram, *A New Kind of Science* (2002), ISBN 1579550088.

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Fringe theories

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Cold fusion

Cold fusion refers to a nuclear fusion process which occurs at or near room temperature, as compared to conventional nuclear fusion, which requires a very hot (100 million degrees) plasma. There are a number of such processes which are under investigation and are generally considered to be scientifically reputable, although none of them have reached anything close to breakeven, including muon-catalyzed fusion and bubble fusion. However, cold fusion is often used to refer to a claimed particular mechanism which is not considered viable by most scientists.

On March 23, 1989, Stanley Pons and Martin Fleischmann at the University of Utah claimed to measure a production of heat that could only be explained by a nuclear process. Steven Jones at Brigham Young University did not observe heat but claimed to observe neutron emission that would also indicate a nuclear process. The claims were particularly astounding given the simplicity of the equipment, just a pair of electrodes connected to a battery and immersed in a jar of heavy water. The immense beneficial implications of the Utah claims, if they were correct, and the ready availability of the required equipment, led scientists around the world to attempt to repeat the experiments within hours of the announcement.

This claim was surrounded by a lot of media attention and excitement which brought the phrase cold fusion into popular consciousness. A few months after the initial cold fusion claims, the Energy Research Advisory Board (part of the US Department of Energy) formed a special panel to investigate cold fusion and the scientists in the panel found the evidence for cold fusion to be unconvincing. [1]

The most common experiments involve a metal electrode (usually palladium or titanium) which has been specially treated so that it is saturated with deuterium and placed in an electrolytic heavy water solution. The experimenters saw extra heat coming from this system which was not readily explained by the electrolytic reaction itself. Although some experiments claimed to see fusion products (tritium, helium, or neutrons) the amount of detected fusion products did not match what was necessary to explain the amount of excess heat. The initial announcement by Pons and Fleischmann in March 1989 exhibited the discrepancy between heat and fusion products in sharp terms. Namely, the level of neutrons they claimed to observe was 10^9 times less than that required if their stated heat output were due to fusion.

The idea that palladium or titanium might catalyze fusion stems from the special ability of these metals to absorb large quantities of hydrogen (or deuterium), the hope being that deuterium atoms would be close enough together to induce fusion at ordinary temperatures. The special ability of palladium to absorb hydrogen was recognized in the nineteenth

century. In the late nineteen-twenties, two German scientists, F. Paneth and K. Peters, reported the transformation of hydrogen into helium by spontaneous nuclear catalysis when hydrogen is absorbed by finely divided palladium at room temperature. These authors later acknowledged that the helium they measured was due to background from the air.

In 1927, Swedish scientist J. Tandberg claimed that he had fused hydrogen into helium in an electrolytic cell with palladium electrodes. On the basis of his work he applied for a Swedish patent for "a method to produce helium and useful reaction energy". After deuterium was discovered in 1932, Tandberg continued his experiments with heavy water. Due to Paneth and Peters' retraction, Tandberg's patent application was denied eventually.

In fact, even though palladium can store large amounts of deuterium, the deuterium atoms are still much too far apart for fusion to occur in normal theories. Actually, deuterium atoms are closer together in D2 gas molecules, which do not exhibit fusion. The closest deuterium-deuterium distance between deuterons in palladium is approximately 0.17 nanometers. This distance is large compared to the bond distance in D2 gas molecules of 0.074 nanometers.

There are still a few people trying to do cold fusion.

Robert L. Park (2000) gives a decent account of cold fusion and its history which represents the perspective of the mainstream scientific community.

Cold fusion is also sometimes used to refer to the well established and reproducible process of muon-catalyzed fusion in which atoms consisting of protons and muons (which are heavy electrons) undergo fusion at low temperatures. In this method of fusion, the muons shield the charges of the protons allows the protons to be close enough to undergo fusion. As presently understood, muon catalysis will not produce net energy in competition with the power required to produce the muons (too few reactions before the muon sticks to a helium nucleus made in the process).

Another table top candidate for fusion is through an extreme form of sonoluminescence, is often called bubble fusion. Natural bubbles of gas inside a liquid would be made to expand to near vacuum, and then collapse. The extreme pressures and temperatures needed for fusion could potentially be reached. Bubble fusion is often associated with cold fusion due to the use of small room temperature containers of acetone (although the fusion process itself would still take place under localised extreme thermonuclear temperatures and pressures). In 2002 bubble fusion attracted a significant amount of media coverage as controversial results were published. As the liquid researchers chose heavy acetone (acetone in which hydrogen atoms had been replaced by heavier deuterium atoms). It was hoped the deuterium atoms would be fused to form helium, releasing energy.

Unlike the cold fusion results of Pons and Fleishman, the bubble fusion results were published in a peer reviewed journal, *Science*. In July of that same year however researchers from the University of Illinois claimed they had discovered chemical reactions in the collapsing bubbles, sapping most of the energy available. Instead of a temperature of millions of degrees, they calculated the temperature within the collapsed bubbles would be closer to 20,000 degrees.

References

Voodoo Science: The Road from Foolishness to Fraud, by Robert L. Park; Oxford University Press, New York; ISBN 0195135156; May 2000.

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Dynamic theory of gravity

Nikola Tesla's **Dynamic Theory of Gravity** was never published. Although Tesla never published his theory, his proposition that gravity is a field effect is now given more serious consideration by physicists than it was at the time he suggested it. At the time, his critique on Einstein's work was considered by the scientific establishment to exceed the bounds of reason.

According to Tesla's biographer, Robert Lomas in his book, *The Man Who Invented the Twentieth Century*, Tesla published a statement on his 81st birthday in 1937, critiquing Einstein's theory of relativity. While this statement indicated that Tesla had "*worked out a dynamic theory of gravity*" that he soon hoped to give to the world, he died before he publicised the details. Few details were revealed by Tesla about his theory. Those that were are basic arguments against space being curved by gravitational effects.

"*... Supposing that the bodies act upon the surrounding space causing curving of the same, it appears to my simple mind that the curved spaces must react on the bodies, and producing the opposite effects, straightening out the curves. Since action and reaction are coexistent, it follows that the supposed curvature of space is entirely impossible - But even if it existed it would not explain the motions of the bodies as observed. Only the existence of a field of forces can account for them and its assumptions dispenses with space curvature. ...* " - Nikola Tesla

As an alternative to Albert Einstein's theory of relativity, Tesla did not accept Einstein's theory equating matter into energy and the converse. The Dynamic theory of gravity was developed initially between 1893 and 1894. The theory reportedly states that the phenomena produced by electromagnetic force is most important phenonomen in the universe.

According to pieces of this theory that can be gathered, mechanical motions are a universally a result of electromagnetic force acting through the mediums. It is the concept that a field of force models phenonomen more precisely. It did not include the curvature of space. This theory is a logical extension of the rotating magnetic field model. The theory refers to an aether similar in terms to conventional electromagnetics. Tesla's aether is *not* analogous to classical aether theories. Sir William Thomson's (i.e., Lord Kelvin) explanation of the aether corresponds closely to Tesla's views of the aether. Tesla's aether are more akin to sound waves. Its properties varied according to velocity, frequency, resonance, the mediums, and the surrounding environment.

Tesla electromagnetics are composed of space-time potentials and their corresponding motion. This potential's motion caused in the surrounding mediums an equivalent and opposite effect (determining the positive and negative character of the medium).

Some elements of the theory may include:

- Electromagnetic energy fills all space-time.

- Electromagnetic fields interact.
- Energy is force over time.
- Mediums are constantly in motion in through space.
- Motion through space produces time.
- Electromagnetic effects produce rotating fields.
- Electromagnetic entropy returns energy to potentials.
- Self-regenerative hetrodyning electromagnetic fields condense in space-time.
- Mediums exposed to resonant vibrations of electromagnetic interact.
- Electromagnetic potentials arrange themselves in groups according to the medium's polarization and the mediums' dielectric resistance.
- Modulating wide band frequencies of electromagnetic phenonomen premeate through all mediums.
- Mediums filling space all possess a dielectric level.
- Electromagnetic force is a phenonomen produced from mediums in space-time.
- Absence of mediums would result in no electromagnetic forces.
- Mechanical effects are produced by electromagnetic forces acting through mediums (i.e., momentum and inertia is electromagnetic)
- Electromagnetic potentials of high frequency produce:
  - lower environmental interaction,
  - uniform movement without rotation through space-time
  - electromagnetic saturation [i.e., plasmas]
- Stationary low frequency electromagnetics behave as waves.
- Medium's electromagnetic fields creates attractive forces from negative polarity [or what is commonly referred to as "gravity"].

It is not clear if the full theory is recorded in any of Tesla's papers, as many of his effects were seized by the United States Federal Government immediately following his death and declared Most Secret to prevent information about other inventions Tesla was working on falling into "*enemy hands*". Papers related to the theory are reportedly classified (e.g., current material released by FOIA have not included these papers).

At the time of his death, Tesla was considered a bizarre crackpot by many, due to his eccentic behaviour. Tesla's reputation as a "mad scientist" in later life means much of his later work was discredited or at least disregarded and ignored by the scientific establishment at the time. His controversial reputation was also exploited by the popular press and only served to enhance it. His "mad scientist" reputation and both the secrecy and the mysterious circumstances surrounding his death have allowed conspiracy theorists to make additional propositions to the theory than Tesla revealed intially.

See also: Physics, Gravity, Theoretical physics, History of physics

Books

- *The Man Who Invented the Twentieth Century: Nikola Tesla, Forgotten Genius of Electricity*, Robert Lomas, Headline Book Publishing, 1999. ISBN 0747262659

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Luminiferous aether

In the late 19th century the **luminiferous aether** ("light-bearing aether") was invoked as the medium for the propagation of light, when it was discovered, from Maxwell's equations, that light is an electromagnetic wave. By analogy to mechanical waves, physicists assumed that electromagnetic waves required a medium for propagation, and hypothesized the aether. Aether was thought to be a fluid which was transparent, non-dispersive, incompressible, continuous, and without viscosity. This idea of an aether has since been rejected by the vast majority of scientists.

Other than the question of propagation, the aether was intended to solve the problem that Maxwell's equations require that electromagnetic waves propagate at a fixed speed, *c*. As this can only occur in one reference frame according to Newtonian physics (see Galilean-Newtonian relativity), the aether was hypothesized as the absolute and unique frame of reference in which Maxwell's equations hold. Later it was regarded as the seat of all electromagnetic energy and attempts were made to describe matter in terms of vortices in this fluid.

Many experiments were conducted to prove the existence of aether. It appeared to be verified by Fresnel's determination that the velocity of light relative to the aether on passing through a medium of refractive index *n* and velocity *v* (in the same direction) is

$$\frac{c}{n} = \left(1 - \frac{1}{n^2}\right) v$$

and in the Airy experiment on aberration. However, this theory required that matter moving through the aether should modify the velocity of the aether and that because of dispersion the relative velocity of medium and aether would be different for different wavelengths, thus requiring a different aether for each wavelength of light.

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Disadvantages and Critics

The key difficulty with the Aether hypothesis arose from the juxtaposition of the two well-established theories of non-relativistic Newtonian dynamics and of Maxwell's electromagnetism. Under a Galilean transformation the equations of Newtonian dynamics are invariant, whereas those of electromagnetism are not. Thus at any point there should be one special coordinate system, at rest relative to the local aether, relative to which Maxwell's equations assume their usual form. Motion relative to this aether should therefore be detectable.

The most famous attempt to detect this relative motion was the Michelson-Morley experiment in 1887, which produced a null result. To explain this apparent contradiction the Lorentz-Fitzgerald contraction hypothesis was proposed but the aether theory was finally abandoned when the Galilean transformation and the dynamics of Newton were modified by Albert Einstein's theory of relativity and when many experiments subsequent to Michelson-Morley failed to find any evidence of aether. Most current physicists do not see a need to have a medium for which light to travel through.

An alternative experiment that tests for the existence of the aether is the Trouton Noble experiment.

Some classic field physicists (like Dayton Miller and Edward Morley) continued research on the aether for some time. There remain some modern proponents of aether theory. Its mystic appeal draws pseudoscientific proponents. Its intuitive appeal draws protoscientific proponents. Its conservative history draws classical field proponents.

It rather easy to create aether theories which conform to the null result of the Michelson-Morley experiment, but it becomes increasing difficult to create theories that are consistent with all of the related experiments which are consistent with no aether. Modern analysis of aether must be consistent with all of the experiments testing phenomena.

Aether theory postulate experiments

- Bradley experiment - aberration of starlight
- Lodge experiment - aether drag
- Fresnel experiment - drag coefficient
- Fizeau experiment - drag coefficient
- Airy experiment - water-filled telescope

Timeline

1818 - Augustin Fresnel's Wave Theory of Light.

1820 - Discovery of Siméon Poisson's "Bright Spot", supporting the Wave Theory.

1873 - James Maxwell's Treatise on Electricity and Magnetism.

1878 to 1880 - Maxwell suggests absolute velocity of Earth in aether may be optically detectable.

1881 - Albert Abraham Michelson publishes first interferometer experiment.

1881 - Hendrik Antoon Lorentz finds Michelson's calculation have errors (i.e., doubling of the expected fringe shift error).

1882 - Michelson acknowledges his interpretation errors.

1887 - Michelson and Edward Williams Morley experiment produces the famous null results.

1887 to 1888 - Heinrich Hertz verifies the existence of electromagnetic waves.

1889 - George Francis FitzGerald proposes the Contraction Hypothesis.

1895 - Lorentz proposes independently another Contraction Hypothesis.

1905 - Miller and Morley's experiment data is published. Test of the Contraction Hypothesis has negative results. Test for aether dragging effects produces null result. Albert Einstein introduces the special theory of relativity.

1919 - Arthur Eddington's Africa eclipse expedition is conducted and appears to confirm the general theory of relativity.

1921 - Dayton Miller conducts aether drift experiments at Mount Wilson. Miller performs tests with insulated and non-magnetic interferometers and obtains positive results.

1921 to 1924 - Miller conducts extensive tests under controlled conditions at Case University.

1924 - Miller's Mount Wilson repeats experiments and yields a positive result.

1925 - Michelson and Gale perform the Pearson experiment producing a null result while attempting to detect the effect of Earth's rotation on the velocity of light. Null result predicted by both relativity and aether theory.

1925 April - Meeting of the National Academy of Sciences.

Arthur Compton explains the Stokes aether drag problems.

Miller Presents his positive results of the aether drag.

1925 December - American Association for the Advancement of Science meeting.

Miller proposes two theories to account for the positive result. It consists of a modified aether theory and a slight departure from the Contraction Hypothesis.

1926 - Roy J. Kennedy produces a null result. Auguste Piccard and Ernest Stahel at Mont Rigi produce a null result.

1927 - K. K. Illingworth produces a null result.

1927 - Mount Wilson conference.

Miller talks of partial entrainment

Michelson talks about aether drag and altitude differential effects

1929 - Michelson and F. G. Pease perform the Pearson experiment and produce a null result.

1930 - Von Georg Joos produces a null result.

1934 - Joos publishes on the Michelson-Gale Results, stating that it is improbable that aether would be entrained by translational motion and not by rotational motion.

1955 - R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti perform a debated analysis of Miller's positive results. Shankland, who led the study, reports statistical fluctuations in the readings and systematic temperature disturbances (both allegations have been later disproven).

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Orgone energy

Wilhelm Reich (March 24, 1897 - November 3, 1957) was an Austrian psychologist trained by Sigmund Freud.

He is known for three things:

- Freud regarded all his theories as unscientific.
- He tried to join Marxism and psychoanalysis in studies of fascism, producing a very popular book, *The Mass Psychology of Fascism*.
- His creation of the mystic pseudoscience of "Reichian Therapy", based on the concept of **orgone energy**, and persecution by the US government of himself and his theories until his death

Reich's development of his orgone theories

During Reich's exile in USA he developed a mystic pseudoscience of "Reichian Therapy", where Freud's concept of the libido has been transformed into orgone, a form of universal power (an "energy field", similar to qi or other semi-mystical energy concepts). Orgone was an unproven form of energy first described by Reich in the late 1930s. Reich characterized orgone as a type of *primordal cosmic energy*, blue in colour, which is omnipresent and responsible for such things as:

- weather,
- the color of the sky,
- gravity,
- the formation of galaxies,
- and good orgasms (the sense of well-being felt after orgasm was supposed by Reich to be due to the orgasm optimising the flow of orgone energy throughout the body.

Reich even speculated that this energy might be used for propulsion of UFOs.

As a consequence of his theory, illness was primarily due to depletion or imbalance in the orgone energy of the body. Reich devised devices known as **orgone accumulators**, which he claimed could concentrate and store orgone energy. Published descriptions of orgone accumulators depict a box made of alternating layers of metal and non-metallic material, with the metal on the interior. The outer, non metallic layer attracted orgone energy, and the metal inner layer trapped it and reflected it within the box: multiple layers amplified the effect. The patient would sit within the accumulator, and absorb the concentrated orgone energy. Reich also devised smaller, more portable accumulators of the same layered construction, for application to parts of the body to promote healing.

At one point Reich claimed the existence of a second form of energy, **oranur** or **DOR** (for "deadly orgone radiation"). DOR seems to be the antithesis of orgone.

Reich designed orgone "guns" called **cloudbusters** to suck DOR from the sky. It has been claimed that they can be used to manipulate the weather and to create rainstorms in a process called *weather engineering*. According to some accounts, the government of Eritrea financed several such projects in the 1980s and 1990s in order to change the weather in the region.

Status of Reich's books

In his book, "The Function of the Orgasm", Reich argued that the "functional" orgasm causes an electrical discharge from the body and a dynamic spasm of the nervous system that are necessary for optimum health. Without such functional orgasms, the body becomes stiff and rigid and develops "body armor". Reich claimed that the masturbatory orgasm does not produce the functional electrical discharge, and that conscious thought during the sexual act prevented the functional orgasm.

Reich's earlier books, in particular his book *The Mass Psychology of Fascism*, are regarded as somewhat scientifically valuable. However, during his later career, Reich subsequently revised his older books to include the orgone concepts. As these are generally regarded unscientific, scholars of psychology and sociology prefer to refer to earlier, German, editions of his works. Any attempts to reprint old editions of his books are blocked by the foundation which owns the rights to Reich's works, which is why they are scarce and hard to find.

Part of the FDA's injunction against Reich's orgone accumulators included any documentation of the accumulators, as well as withholding any of his existing books from publication until mention of orgone energy was expunged from them. This has caused many to levy charges against the United States government of censorship of Reich's ideas. In the late 1960s and early 1970s Reich's ideas enjoyed a revival and most of his books were reprinted and read by the loosely defined "New Left". As of 2003, the majority of the scientific community dismisses Reich's claims as *pseudoscientific*. Many people view Reich's theories as a system of magic.

The orgone accumulator and the cloudbusters are now mostly remembered for the songs of the same name by Hawkwind, Pop Will Eat Itself and Kate Bush.

Bibliography

By Reich

- *Der triebhafte Charakter : eine psychoanalytische Studie zur Pathologie des Ich*, 1925
- *Die Funktion des Orgasmus : zur Psychopathologie und zur Soziologie des Geschlechtslebens*, 1927
- *Über den Ödipuskomplex : drei psychoanalytische Studien* with Felix Boehm and Otto Fenichel, 1931
- *Character analysis* or in the original: *Charakteranalyse : Technik und Grundlagen für studierende und praktizierende Analytiker*, 1933
- *The Mass Psychology of Fascism* - even the 1946 USA edition is regarded as bogus in scientific contexts, what should be referred to is the German 1933 edition of *Massenpsychologie des Faschismus : zur Sexual Sexualökonomie der politischen Reaktion und zur proletarischen Sexualpolitik* which was banned in Nazi Germany.

About Reich

- *Fury on Earth* Myron Sharaf
- *Reich for Beginners* David Zane Mairowitz

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Reciprocal System of Theory

The **Reciprocal System of Theory (RST)** is held by advocates to be a theoretical framework capable of comprehensively explaining all physical phenomena from subatomic particles to galactic clusters. The framework, based on the work of Dewey B. Larson, an American engineer and author, was originally described in his book *The Structure of the Physical Universe* in 1959 and has more recently been published in three revised and enlarged volumes. The ideas are promoted by the members of 'The International Society of Unified Science, Inc.' (ISUS) whose only stated objective is to "advance in all ways deemed feasible the Reciprocal System of physical theory as proposed by Dewey B. Larson".

The RST and the work of Larson assumes that the basic constituent of the universe is motion (i.e. space & time), not matter. Thus, it is a unique approach in the science of physics. However, so far, it has remained essentially unknown or ignored in the mainstream physics community, since it is completely at odds with current theories such as relativity, quantum mechanics and the Big Bang and many other modern theories. Although it is generally dismissed by those physicists who are aware of it, proponents claim that it rests on solid philosophical grounds, and that it is the first general theory of physics ever developed. Unlike conventional theory, they point out, the RST has no empirical content, but rather all its conclusions are based *solely* on its initial assumptions. These initial assumptions are contained in only two brief statements that Larson designated the "Fundamental Postulates" of the system, namely:

1) The physical universe is composed entirely of one component, motion, existing in three dimensions, in discrete units, and with two reciprocal aspects, space and time.

2) The physical universe conforms to the relations of ordinary commutative mathematics, its magnitudes are absolute and its geometry is Euclidean.

From the first postulate, Larson concludes that while both space and time are three dimensional, or, in other words that it takes three magnitudes to completely specify them, they can have no physical significance other than what they have in the equation of motion. Therefore, it follows that space is not an independent entity that can be affected by matter in any respect. Considered apart from motion, space is only a concept, or mental construct, which can be utilized to devise a convenient system of reference for measurement purposes. Likewise, time is not an independent physical entity that can be considered apart from motion. Space and time only have meaning as reciprocal aspects of motion.

Larson further concludes from the first postulate that, since the postulated three-dimensionional motion is assumed to exist in discrete units, the dimensions of motion are therefore independent. This means that independent two-dimensional and one-dimensional motion are also possible. In fact, in the due course of the theory's development, Larson shows that quantities of one-dimensional motion correspond to electric potential, quantities of two-dimensional motion correspond to magnetic potential, and quantities of three-dimensional motion correspond to gravitational potential. Larson argues that this is the basis for explaining many otherwise unexplainable electrical and magnetic phenomena such as induction (in general, 2D motion (magnetic motion) cancels a portion of 3D motion (matter) leaving a 1D motion residue (electric motion), or, alternately, 1D motion (electric motion) cancels a portion of 3D motion (matter) leaving a 2D motion residue (magnetic motion)).

Of course, this theroetical approach of a universe consisting of nothing but motion (space and time) constitutes a completely new paradigm that departs radically from the current paradigm of a universe consisting of matter *contained* in space and time. This is most simply illustrated in the difference between Einstein's conclusion, called the Equivalence Principle, that the force of gravity is *equivalent* to an acceleration, and Larson's conclusion that the force of gravity *is* an acceleration. Another example is Einstein's conclusion that matter and energy are *equivalent.* Larson asserts that this leads to a contradiction at high speeds, which is resolved by the conclusion that matter and energy are not equivalent, but interconvertable, meaning matter can be converted to energy and vice-versa, but the two are distinct degrees of motion (matter is 3D motion, while energy is 1D motion.) These are just two of the many cases where the concepts of the different paradigms lead to conflicting conclusions; there are many others.

For instance, the RST concludes unequivocally that gravitational radiation, a requirement of general relativity, cannot exist, and that gravity operates without any medium or continuum such as the four-dimensional (4D), curved-space of relativity, or any process of transmission between gravitating bodies. Although this is in accord with current observations, it is at odds with existing indirect evidence for the existence of gravitational radiation, from binary neutron star measurements. While General relativity (GR) predicts that, due to gravitational radiation, the orbit of such systems will decay at a specific rate, the RST attributes the force of gravity to the inherent 3D inward motion of the mass of gravitating bodies. In this way the same motion that constitutes the mass of a body also produces the force of gravity associated with that mass. No energy transmission process is involved in this phenomenon, and, thus, no orbital decay should result from its operation.

However, an orbital decay *is* observed in these binary star systems, and the rate of decay *is* as predicted by general relativity, to an accuracy of 0.5%. On the other hand, it must be conceded that these systems are not well understood, and definite conclusions are premature at this point. For instance, at least one system (PSR B1744-24A,) is exhibiting an orbital decay of five times the rate attainable through gravitational radiation. Fortunately, new gravitational wave detectors, such as LIGO, VIRGO, LISA and others, are soon expected to detect gravitational radiation directly, which promises to settle the matter definitively.

Meanwhile, RST proponents claim that the theory is also consistent with recent observations that the geometry of the universe is flat (from the CMB data), and that the cosmological parameter, Omega, is precisely equal to one. These data are in conflict with traditional Big Bang cosmology, where Euclidean geometry would appear to be highly unlikely. While the theory of cosmic inflation is the method accepted by most physicists for overcoming this apparent contradiction, the fact that such *ad hoc* theories are necessary at all, is *prima facia* evidence, say RST proponents, of the problems experienced in current physical theories, which they complain are, as Richard Feynman said, *"a multitude of different parts and pieces that do not fit together very well."*

The most embarrassing example of this predicament, advocates say, is the recent discovery of the accelerating expansion of the universe. The observed acceleration is thought to be produced by a gravity-like repulsive force. Some think that this force, dubbed "dark energy," by Michael Turner of the University of Chicago, might be vacuum energy, represented by the "cosmological constant" (») in general relativity or possibly something called "Quintessence." While this new positive force is thought to be similar to the negative force of gravity, its existence is in conflict with established theories. However, a similar outward, gravity-like motion has been an integral part of the RST from the beginning, and is a major component in the RST's calculations and explanations of both the large-scale structure of the universe and its atomic and molecular scale structure. It plays a fundamental role in the RST's explanation of the recession of galaxies, star formation, galaxy formation and the explosions of stars, without the need for the "Big Bang," or black holes to explain these processes. Of course, the RST is not necessary to explain this outward motion--Einstein himself proposed the expedient of inserting a cosmological constant into his equations soon after he proposed the theory of relativity, and, even today, mainstream scientists are exploring new *ad hoc* theories of expansion to address the problem and explain the observations without the need for the RST, but, the proponents emphasize, theoretical adjustments such as these cannot be made in the RST as everything in it must follow from the consequences of its fundamental postulates. Needless to say, such a claim sets the RST apart as very unusual and extremely unorthodox.

Other examples of unusual and unorthodox theoretical conclusions reached in the RST include the derivation of a non-nuclear model of the atom in *Nothing But Motion*, which leads directly to the periodic order of the elements. Larson claims that his theory accurately derives the elements in *correct order* without employing the nuclear concept of electrons orbiting an atomic nucleus, and predicts that the *maximum* number of elements in the periodic table is 117. However, his theory has not yet accounted for the atomic spectra of the elements. In contrast, the extremely accurate results obtained by quantum mechanics and the nuclear model of the atom are well known.

On the other hand, in *Basic Properties of Matter*, Larson makes theoretical predictions for a large number of properties of a range of chemical species, including atomic mass, interatomic distance, compressibility and heat capacity. It appears that he calculates these values from simple closed-form analytic formulas. If accurate, this would be a vast improvement on the complex calculations required to make theoretical predictions under quantum mechanics. For instance, using the RST non-nuclear model of the atom, Larson begins with calculations of inter-atomic distances of the elements. These distances, which in the RST are a result of an equilibrium reached between two opposing, non-electronic forces, are calculated by an equation derived from the "specific" motion of the atom's combination of motions in several dimensions. In it's simplest form, applicable to the noble elements, where there are only two such specific motions involved, the equation is:

$$s_o = 2.914 \ln t \text{ angstroms}$$

where s_o is the center-to-center distance in angstrom units and t is the specific motions of the elements. Where these two specific motions are equal, only 1 of them enters into the calculation. However, if they are unequal, a single value is obtained by squaring the first and taking the cube root of its product with the second:

$$t = (t^2 t)^{1/3}$$

On this basis, the result for Neon, with its two specific rotations of 3 and 3 is exceedingly simple to calculate:

$$s_o = 2.914 * \ln t = 2.914 * \ln 3 = 2.914 * 1.098612 = 3.201355 \text{ angstroms}$$

This value compares with an observed value of 3.17 angstroms for Neon (see webelements.com.) The calculated values of the other noble elements for which data is available are also quite comparable. For instance, the calculation of Argon is 3.76 angstroms, which compares to an observed value of 3.72 angstroms; the value for Krypton is 4.04, compared to 4.04 observed; and 4.38 for Xenon, compared to 4.39 observed.

However, in many cases Larson must modify the equations to be used, changing them from species to species on grounds difficult for non-initiates to easily follow without further study. For example, Larson lists characteristic values for the various species which are specific to the RST, such as "specific electric rotation". Because the basis for the procedure for calculating these values is explained in an earlier volume of the work, it is necessary to devote a great deal of time to the study of the RST to rule out the allegation that they were selected arbitrarily to make the predictions fit the data. Nevertheless, it's interesting to note that Larson's calculations of the values shown above, except for Neon, are closer to the accepted values today than when he published them in the early 1980s.

According to its proponents, the RST can also be used to solve the famous problem of the precession of the perihelion of the planet Mercury. This problem was first solved using Einstein's equations of general relativity, which assumes relative values of space-time in the equations of motion, as opposed to Newton's assumption that space and time should be treated as absolute concepts in the equations of motion. Larson, in the RST, also assumes absolute values of space and time, but goes beyond Newton in the definition of these crucial concepts. Using these definitions, K.V.K. Nehru produced a paper describing the orbital motion of high-speed planets. The result he found from the RST was precisely the same as that from relativity. Hence, like general relativity, the RST is fully in agreement with accurate measurements of Mercury's orbit.

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Steady state theory

The **steady state theory** was developed in 1949 by Fred Hoyle and others as an alternative to the Big Bang theory. According to the steady state theory, although the universe is expanding, it nevertheless does not change its look over time, because new matter is formed to keep the density equal. Because only very little matter needs to be formed, roughly a few hundred atoms of hydrogen in the Milky Galaxy each year, it is not a problem of the theory that the forming of matter is not observed directly.

Problems with the steady state theory began to emerge in the late 1960s, when evidence started to show that the universe was in fact changing: quasars and radio galaxies were found only at large distances (and thus, because of the finiteness of the speed of light, in the past), not in closer galaxies. The final blow came with the discovery of the cosmic background radiation in 1965 which was predicted by the big bang theory, and not the steady state theory.

Today, the big bang theory is the one that astronomers consider a good approximation to describing the origin of the universe and the basis of more complete theories.

Observational cosmologists deal with observations, and because the universe and the speed of light are both finite, one can only observe data within a sphere centered on the observers. What is outside that sphere is therefore not accessible to observational cosmologists.

Theoretical cosmologists regard the big bang model as incomplete in part because it does not address the issue of what happened before the big bang. Some of these speculations about what happened before the big bang and what would happen after the big crunch are qualitatively somewhat similar to the quasi-steady-state-model.

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Concepts

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Matter

One contemporary view on **matter** takes it as all scientifically observable entities whatsoever. Commonly, the definition is limited to such entities explored by physics.

The definition pursued here is of **matter** as whatever the smallest, most fundamental entities in physics seem to be. Thus matter can be seen as material consisting of particles which are fermions and therefore obey the Pauli exclusion principle, which states that no two fermions can be in the same quantum state. Because of this principle, the particles which comprise matter do not all end up in their lowest energy state, and hence it is possible to create stable structures out of fermions. In addition, the Pauli exclusion principle insures that two pieces of matter will not occupy the same location at the same time, and therefore two pieces of matter in which most energy states are filled will tend to collide with each other rather than passing through each other as with energy fields such as light.

The matter that we observe most commonly takes the form of compounds, polymers, alloys, or pure elements.

In response to different thermodynamic conditions such as temperature and pressure, matter can exist in different "phases", the most familar of which are solid, liquid, and gas. Others include plasma, superfluid, and Bose-Einstein condensate. When matter changes from one phase to another, it undergoes what is known as a phase transition, a phenonmenon studied in the field of thermodynamics.

See also

- particle physics, which provides a bit of historical background

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Antimatter

Antimatter is matter that is composed of the antiparticles of those that constitute normal matter. An atom of anti-hydrogen, for instance, is composed of a negatively-charged antiproton being orbited by a positively-charged positron. If a particle/antiparticle pair comes in contact with each other, the two annihilate in a burst of electromagnetic radiation.

With antimatter, the entire possible energy of the matter could be harnessed, instead of the very small chemical energies or nuclear energies that can be extracted today. The reaction of 1 kg of antimatter with 1 kg of matter would produce 1.8×10^{17} J of energy (by the

equation $E=mc^2$). In contrast, burning a kilogram of petrol produces 4.2×10^7 J, and nuclear fusion of a kilogram of hydrogen would produce 2.6×10^{15} J.

Since the energy density is vastly higher than these other forms, the thrust to weight equation used in antimatter rocketry and spacecraft would be very different. In fact, the energy in a few grams of antimatter is enough to transport a small ship to the moon. It is hoped that antimatter could be used as fuel for interplanetary travel or possibly interstellar travel, but it is also feared that if humanity ever gets the capabilities to do so, there could be the construction of antimatter weapons.

Scientists succeeded in 1995 to produce anti-atoms of hydrogen, and also anti-deuteron nuclei, made out of an anti-proton plus an anti-neutron, but not yet more complex antimatter. Also, they exist for a very short time, they can not be stored. As far as we know there are no antimatter atoms in existence in this universe outside of our particle physics labs. This is a great mystery since one would expect matter and antimatter to have been generated in equal amounts after the Big Bang. The scarcity of antimatter has given us a stable universe, however, without which life could not have evolved.

The scarcity of antimatter means that it is not readily available to be used as fuel. Generating a single atom of antimatter is immensely difficult and requires particle accelerators and vast amounts of energy - millions of times more than is released after it is annihilated with ordinary matter, due to inefficiencies in the process. No more than a handful of antimatter atoms have ever been made. Therefore, unless substantial quantities from some as-yet unimagined natural source of antimatter are found, or ways to generate antimatter more efficiently are determined, antimatter will remain a curiosity rather than a viable propulsion system.

The symbol used to denote an antiparticle is the same symbol used to denote its normal matter counterpart, but with an overstrike. For example, a proton is denoted with a "p", and an antiproton is denoted by a "p" with a line over its top ($\bar{p}$).

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Elementary particle

In particle physics, an **elementary particle** refers to a particle of which other, larger particles are composed. For example, atoms are made up of smaller particles known as electrons, protons, and neutrons. The proton and neutron, in turn, are composed of more elementary particles known as quarks. One of the outstanding problems of particle physics is to find the most elementary particles - or the so-called **fundamental particles** - which make up all the other particles found in Nature, and are not themselves made up of smaller particles.

The Standard Model of particle physics contains 12 species of elementary fermions ("matter particles") and 12 species of elementary bosons ("radiation particles"), plus their corresponding antiparticles. However, the Standard Model is widely considered to be a provisional theory rather than a truly fundamental one, and it is possible that some or all of its "elementary" particles are actually composite particles. There might also be other elementary particles not described by the Standard Model, the most prominent being the graviton, the hypothetical particle that carryies the gravitational force.

See also

- Particle physics

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Boson

Bosons, named after Satyendra Nath Bose, are particles which form totally-symmetric composite quantum states. As a result, they obey Bose-Einstein statistics. The spin-statistics theorem states that bosons have integer spin.

All elementary particles are either bosons or fermions.

Guage bosons are elementary particles which act as the carriers of the fundamental forces.

Particles composed of a number of other particles (such as protons or nuclei) can be either fermions or bosons, depending on their total spin. Hence, many nuclei are in fact bosons. While fermions obey the Pauli exclusion principle: "*no more than one fermion can occupy a single quantum state*", there is no exclusion property for bosons, which are free to (and indeed, other things being equal, *tend* to) crowd into the same quantum state. This explains the spectrum of black-body radiation and the operation of lasers, the properties of liquid Helium-4 and superconductors and the possibility of bosons to form Bose-Einstein condensates, a particular state of matter.

Examples of bosons:

- photons, which mediate the electromagnetic force

- W and Z bosons, which mediate the weak nuclear force
- liquid Helium
- Cooper pair

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Fermion

All elementary particles are either **fermions** or bosons.

Fermions, named after Enrico Fermi, are particles which form totally-antisymmetric composite quantum states. As a result, they are subject to the Pauli exclusion principle and obey Fermi-Dirac statistics. The spin-statistics theorem states that fermions have half-integer spin.

The elementary particles which make up matter are fermions, predominantly quarks (which form protons and neutrons) and electrons. These elementary fermions are classified into two groups: leptons and quarks.

Examples of fermions:

- electrons
- protons
- neutrons
- quarks

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Energy

From the perspective of physics, every physical system contains (alternatively, stores) a certain amount of a continuous, scalar quantity called **energy**; exactly how much is determined by taking the sum of a number of special-purpose equations, each designed to quantify energy stored in a particular way. There is no uniform way to visualize energy; it is best regarded as an abstract quantity useful in making predictions.

The first sort of prediction energy allows one to make is how much work a physical system could be made to do. Performing work requires energy, and thus the amount of energy in a system limits the maximum amount of work that a system could conceivably perform. In the one-dimensional case of applying a force through a distance, the energy required is + f(x) dx, where f(x) gives the amount of force being applied as a function of the distance moved.

Note, however, that not all energy in a system is stored in a recoverable form; thus, in practice, the amount of energy in a system available for performing work may be much less than the total amount of energy in the system.

Energy also allows one to make predictions across problem domains. For example, if we assume we are in a closed system (i.e. the conservation of energy applies), we can predict

how fast a particular resting body would be made to move if a particular amount of heat were completely transformed into motion in that body. Similarly, it allows us to predict how much heat might result from breaking particular chemical bonds.

The SI unit for both energy and work is the joule (J), named in honor of James Prescott Joule and his experiments on the mechanical equivalent of heat. In slightly more fundamental terms, 1 joule is equal to 1 newton metre, and in terms of SI base units, 1 J equals 1 kg m^2/s^2. (*Conversions.* In cgs units, one erg is 1 g cm^2/s^2. The imperial/US unit for both energy and work is the foot pound.)

Noether's theorem relates the conservation of energy to the time invariance of physical laws.

Energy is said to exist in a variety of forms, each of which corresponds to a separate energy equation. Some of the more common forms of energy are listed below.

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Kinetic energy

Kinetic energy is that portion of energy associated with the motion of a body.

$$KE = + \mathbf{v} \cdot d\mathbf{p}$$

For non-relativistic velocities, we can use the Newtonian approximation

$$KE = 1/2\ mv^2$$

(where KE is kinetic energy, m is mass of the body, v is velocity of the body)

At near-light velocities, we use the relativistic formula:

$$KE = m_o c^2(^3 - 1) = {}^3 m_o c^2 - {}_o c^2 :^3 = (1 - (v/c)^2)^{-1/2}$$

(where v is the velocity of the body, m_o is its rest mass, and c is the speed of light in a vacuum.)

The second term, mc^2, is the rest mass energy and the first term, $^3mc^2$ is the total energy of the body.

Heat

Heat is related to the internal kinetic energy of a mass, but it is not a form of energy. Heat is more akin to work in that it is a change in energy. The energy that heat represents a change specifically refers to the energy associated with the random translational motion of atoms and molecules in some identifiable mass. The conservation of heat and work form the First law of thermodynamics.

Potential energy

Potential energy is energy associated with being able to move to a lower-energy state, releasing energy in some form. For example a mass released above the Earth has energy resulting from the gravitational attraction of the Earth which is transferred in to kinetic energy.

Equation:

$$E_p = mhg$$

where m is the mass, h is the height and g is the value of acceleration due to gravity at the Earth's surface.

Chemical energy

Chemical energy a form of potential energy related to the breaking and forming of chemical bonds.

Electrical energy

Electromagnetic radiation

See electromagnetic radiation.

Mass

In the theory of relativity, the energy E of a particle is related to its momentum p and mass m by:

$$E^2 = m^2c^4 + p^2c^2$$

where c is the speed of light. This equation shows that the mass provides a contribution to the energy. Even if p is zero, the particle has a *rest energy* that is nonzero if the mass is nonzero. The rest energy is

$$E_0 = m'c^2$$ **(i.e. 90 petajoule/kg)**

See also: Entropy, Thermodynamics

Further reading

- Feynman, Richard. *Six Easy Pieces: Essentials of Physics Explained by Its Most Brilliant Teacher*. Helix Book. See the chapter "conservation of energy" for Feynman's explanation of what energy is, and how to think about it.

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Symmetry

Symmetry is a characteristic of geometrical shapes, equations and other objects; we say that such an object is *symmetric* with respect to a given operation if this operation, when applied to the object, does not appear to change it. The three main symmetrical operations are reflection, rotation and translation. A reflection "flips" an object over a line, inverting it as if in a mirror. A rotation rotates an object using a point as its center. A translation "slides" an object from one area to another by a vector. Even more complex operations on a geometric object, like shrinking or shape warping, can be reduced to the operation of translation of every point within the object. Symmetry occurs in geometry, mathematics, physics, biology, art, literature (palindromes), etc.

Although two objects with great similarity appear the same, they must logically be different. For example, if one rotates an equilateral triangle around its center 120 degrees, it will appear the same as it was before the rotation to an observer. In theoretical euclidean geometry, such a rotation would be unrecognizable from its previous form. In reality however, each corner of any equilateral triangle composed of matter must be composed of separate molecules in separate locations. Symmetry therefore, is a matter of similarity instead of sameness. The difficulty for an intelligence to differentiate such a seemingly exact similarity might be responsible for the mild altered state of consciousness one gets by observing intricate patterns based on symmetry.

Symmetry in physics

The generalisation of symmetry in physics to mean invariance under any kind of transformation has become one of the most powerful tools of theoretical physics. See Noether's theorem for more details. This has led to group theory being one of the areas of mathematics most studied by physicists.

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Motion

In physics, **motion** means a change in the position of a body with respect to time, as measured by a particular observer in a particular frame of reference. Until the end of the 19th century, Newton's laws of motion, which he posited as axioms or postulates in his famous *Principia,* were the basis of what has since become known as classical physics. Calculations of trajectories and forces of bodies in motion based on Newtonian or classical physics were very successful until physicists began to be able to measure and observe very fast physical phenomena.

At very high speeds, the equations of classical physics were not able to accurately calculate correct values. To address these problems, the ideas of Albert Einstein concerning the fundamental phenomena of motion were adopted in lieu of Newton's. Whereas Newton's laws of motion assumed absolute values of space and time in the equations of motion, Einstein's theories assumed relative values for these concepts. Since Einstein's equations yielded accurate results at high speeds and Newton's did not, the concept of relativity was established in modern theoretical physics, and Einstein's theory of relativity for bodies in motion has usurped Newton's laws of motion, based on absolute space and time. However, as a practical matter, Newton's equations are much easier to work with than Einstein's and therefore are more often used in applied physics and engineering.

It is interesting to note, however, that because motion is defined as the proportion of space to time, these concepts are prior to motion, just as the concept of motion itself is prior to force. In other words, the properties of space and time determine the nature of motion and the properties of motion, in turn, determine the nature of force. Therefore, relative space and relative time result in relative motion, which means that the unit values of space and time can change for observers moving at high speeds relative to each other. These concepts have led physicists in general to conclude that only relative motion can be measured and that absolute motion is meaningless. See also equation of motion, Newton's laws of motion.

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Conservation laws

In physics, a **conservation law** states that a particular measurable property of an isolated physical system does not change as the system evolves. The following list is a partial listing of conservation laws that have never been shown to be inexact:

- conservation of energy (including mass)
- conservation of mass
- conservation of momentum
- conservation of angular momentum
- conservation of electric charge
- conservation of color-charge
- conservation of magnetic flux

There are more subtle conservation laws in particle physics like those of spin, baryon number and more recently strangeness.

Noether's theorem expresses the equivalence which exists between conservation laws and the invariance of physical laws with respect to certain transformations (typically called "symmetries") (This only applies to systems describable by a Lagrangian). There is an analogous theorem for Hamiltonian mechanics. For instance, time-invariance implies that energy is conserved, translation-invariance implies that momentum is conserved, and rotation-invariance implies that angular momentum is conserved.

Some conservation laws hold in many circumstances, but exceptions to them have been observed. Such is the violation of parity conservation; apparently the universe has "handedness" (right versus left).

Philosophy of Conservation Laws

- *Things that remain unchanged, in the midst of change*

The idea that some things remain unchanging throughout the evolution of the universe has been motivating philosophers and scientists alike for a long time.

In fact, quantities that are conserved, *the invariants*, seem to preserve what one would like to call some kind of a 'physical reality' and seem to have a more meaningful existence than many other physical quantities. These laws bring a great deal of simplicity into the structure of a physical theory. They are the ultimate basis for most solutions of the equations of physics.

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Mass

Mass is a property of physical objects which, roughly speaking, measure the amount of matter contained in an object. It is a central concept of classical mechanics and related subjects. In the SI system of measurement, mass is measured in kilograms.

Strictly speaking, mass refers to two quantities:

- *Inertial mass* is a measure of an object's inertia, which is its resistance to changing its state of motion when a force is applied. An object with small inertial mass changes its motion more readily, and an object with large inertial mass does so less readily.
- *Gravitational mass* is a measure of the strength of an object's interaction with the gravitational force. Within the same gravitational field, an object with a smaller gravitational mass experiences a smaller force than an object with a larger gravitational mass. (This quantity is sometimes confused with weight.)

Inertial and gravitational mass have been experimentally shown to be equivalent, as accurately as we can measure, although they are conceptually quite distinct. Below, we will discuss the definitions and implications of each of these two quantities.

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Inertial Mass

Inertial mass is determined using Newton's second and third laws of motion (see classical mechanics.) Given an object with a known inertial mass, we can obtain the inertial mass of any other object by making the two objects exert a force on each other. According to Newton's third law, the forces experienced by each object will have equal magnitude. This allows us to study how the two objects resist similar applied forces.

Suppose we have two objects, A and B, with inertial masses m_A (which is known) and m_B (which we wish to determine.) We will assume these masses to be constant. We isolate the two objects from all other physical influences, so that the only forces present are the force exerted on A by B, which we denote $\mathbf{F}_{AB}$, and the force exerted on B by A, which we denote $\mathbf{F}_{BA}$. According to Newton's second law,

$$F_{AB} = m_A a_A$$
$$F_{BA} = m_B a_B.$$

where $\mathbf{a}_A$ and $\mathbf{a}_B$ are the accelerations of A and B respectively. To proceed, we must ensure that these accelerations are non-zero, i.e. that the forces between the two objects are non-zero. This may be done, for example, by having the two objects collide and performing our measurements during the collision.

Newton's third law states that the two forces are equal and opposite, i.e.

$$F_{AB} = - F_{BA}.$$

When substituted into the above equations, this yields the mass of B as

$$m_B = \frac{a_A}{a_B} m_A.$$

Thus, measuring $\mathbf{a}_A$ and $\mathbf{a}_B$ allows us to determine m_A in terms of m_B, as desired. Note that our above requirement, that $\mathbf{a}_B$ be non-zero, allows this equation to be well-defined.

In the above discussion, we assumed that the masses of A and B are constant. This is a fundamental assumption, known as the conservation of mass, and is based on the expectation that matter can never be created or destroyed, only split up or recombined. (The implications of special relativity are discussed below.) It is sometimes useful to treat the mass of an object as changing with time: for example, the mass of a rocket decreases as the rocket fires. However, this is an approximation based on ignoring pieces of matter which enter or leave the system. In the case of the rocket, these pieces correspond to the ejected propellent; if we were to measure the total mass of the rocket and its propellent, we would find that it is conserved.

Gravitational Mass

Consider two objects A and B with gravitational masses M_A and M_B, at a distance of $|\mathbf{r}_{AB}|$ apart. Newton's law of gravitation states that the magnitude of the gravitational force which each object exerts on the other is

$$|F| = \frac{GM_AM_B}{|r_{AB}|}$$

where G is the universal gravitational constant. The above statement may be reformulated in the following way: given the acceleration **g** of a reference mass in a gravitational field (such as the gravitational field of the Earth), the gravitational force on an object with gravitational mass M has magnitude

$$|F| = Mg.$$

This is the basis by which masses are determined by weighing. In simple bathroom scales, for example, the force $|\mathbf{F}|$ is proportionate to the displacement of the spring beneath the weighing pan (see Hooke's law), and the scales are calibrated to take **g** into account, allowing the mass M to be read off.

Equivalence of Inertial and Gravitational Masses

Experiments have found inertial and gravitational mass to be equal, to a high level of precision. These experiments are essentially tests of the well-known phenomenon, first observed by Galileo, that objects fall at a rate irrespective of their masses (in the absence of factors such as friction.) Suppose we have an object with inertial and gravitational masses m and M respectively. If gravity is the only force acting on the object, the combination of Newton's second law and gravitational law gives its acceleration **a** as

$$a = \frac{M}{m}g$$

Therefore, all objects in the same gravitational field fall at the same rate if and only if the ratio of gravitational and inertial mass is always equal to some fixed constant. We may as well take this ratio to be 1, by definition.

Consequences of Relativity

In the special theory of relativity, "mass" refers to the inertial mass of an object as measured in the frame of reference in which it is at rest (which is known as its "rest frame".) The above method for determining inertial masses remains valid, provided we ensure that the speed of the object is always much smaller than the speed of light, so that classical mechanics is valid.

Historically, the term "mass" was used for the quantity E/c^2. This was called the "relativistic mass", and m called the "rest mass". This terminology is now discouraged by physicists, because there is no need for two terms for the energy of a particle, and because it creates confusion when speaking of "massless" particles. In this article, we will always mean the *rest mass* whenever we refer to "mass". For more details, see the Usenet Relativity FAQ in the External Links.

In relativistic mechanics, the mass of a free particle is related to its energy and momentum by the following equation:

$$\frac{E^2}{c^2} = m^2c^2 + p^2.$$

This equation can be rearranged in the following way:

$$E = mc^2\sqrt{1 + (\frac{p}{mc})^2}$$

The classical limit corresponds to the situation in which the momentum *p* is much smaller than *mc*, in which case we can Taylor expand the square root, resulting in

$$E = mc^2 + \frac{p^2}{2m} + ...$$

The leading term, which is the largest, is the *rest energy* of the particle. Provided the mass is non-zero, a particle always has this minimum amount of energy regardless of its momentum. The rest energy is normally inaccessible, but it can be tapped by splitting or combining particles, as is done during nuclear fusion and fission. The second term is simply the classical kinetic energy, which can be demonstrated by using the classical definition of momentum

$$p = mv$$

and substituting it into the above to give:

$$E = mc^2 + \frac{mv^2}{2} + ...$$

The relativistic energy-mass-momentum relation can also account for particles that are *massless*, which is an ill-defined concept in classical mechanics. When $m = 0$, the relation can be simplified to

$$E = pc$$

where *p* is the relativistic momentum.

This equation governs the mechanics of massless particles such as photons, the particles of light.

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Momentum

Momentum is the Noether charge of translational invariance. As such, even fields as well as other things can have momentum, not just particles. However, in curved spacetime which isn't asymptotically Minkowski, momentum isn't defined at all.

In physics, **momentum** is a physical quantity related to the velocity and mass of an object.

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Momentum in classical mechanics

In classical mechanics, momentum (traditionally written as ***p***) is defined as the product of mass and velocity. It is thus a vector quantity.

The SI unit of momentum is newton-seconds, which can alternatively be expressed with the units kg.m/s.

An impulse changes the momentum of an object. An impulse is calculated as the integral of force with respect to duration.

$$I = \int F\,dt$$

using the definition of force yields:

$$I = \int \frac{dp}{dt}\,dt$$

$$I = \int dp$$

$$I = ”p$$

See also angular momentum.

Momentum in relativistic mechanics

It is commonly believed that the physical laws should be invariant under translations. Thus, the definition of momentum was changed when Einstein formulated Special relativity so that its magnitude would remain invariant under relativistic transformations. See physical conservation law. We now define a vector, called the **4-momentum** thus:

$$[E/c\ \mathbf{p}]$$

where E is the total energy of the system, and ***p*** is called the "relativistic momentum" defined thus:

$$E = {}^3mc^2$$

$$\mathbf{p} = {}^3m\mathbf{v}$$

and

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

Setting velocity to zero, one derives the result that objects have a rest mass which is related by the experession E=mc^2

The "length" of the vector that remains constant is defined thus:

$$p \cdot p - E^2$$

Massless objects such as photons also carry momentum; the formula is $\boldsymbol{p}=E/c$, where E is the energy the photon carries and c is the speed of light.

Momentum in quantum mechanics

In quantum mechanics momentum is defined as an operator on the wave function. The Heisenberg uncertainty principle defines limits on how accurately the momentum and position of a single observable system can be known at once.

Figurative use

A process may be said to **gain momentum**. The terminology implies that it requires effort to start such a process, but that it is relatively easy to keep it going.

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Angular momentum

In physics, **angular momentum** intuitively measures how much the linear momentum is directed around a certain point called the origin; the moment of momentum. Since angular momentum depends upon the origin of choice, one must be careful when discussing angular momentum to specify the origin and not to combine angular momenta about different origins.

The traditional mathematical definition of the angular momentum of a particle about some origin is:

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

where **L** is the angular momentum of the particle, **r** is the position of the particle expressed as a displacement vector from the origin, and **p** is the linear momentum of the particle. If a system consists of several particles, the total angular momentum about an origin can be gotten by adding (or integrating) all the angular momenta of the constituent particles.

For many applications where one is only concerned about rotation around one axis, it is sufficient to discard the vector nature of angular momentum, and treat it like a scalar where it is positive when it corresponds to a counter clock-wise rotations, and negative clock-wise. To do this, just take the definition of the cross product and discard the unit vector, so that angular momentum becomes:

$$L = |\mathbf{r}||\mathbf{p}|\sin¸$$

where ¸ is the angle between **r** and **p** measured from **r** to **p**; an important distinction because without it, the sign of the cross product would be meaningless. From the above, it is possible to reformulate the definition to either of the following:

$$L = \pm|\mathbf{p}||\mathbf{r}_{\text{perpendicular}}|$$

where $\mathbf{r}_{\text{perpendicular}}$ is called the *lever arm distance* to **p**. The easiest way to conceptualize this is to consider the lever arm distance to be the distance from the origin to the line that **p** travels along. With this definition, it is necessary to consider the direction of **p** (pointed clock-wise or counter clock-wise) to figure out the sign of L). Equivalently:

$$L = \pm|\mathbf{r}||\mathbf{p}_{\text{perpendicular}}|$$

where $\mathbf{p}_{\text{perpendicular}}$ is the component of **p** that is perpendicular to **r**. As above, the sign is decided base on the sense of rotation.

In analogy to Newton's second law for linear momentum, we have the following law about angular momentum:

$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\tau}$$

where **Ä** is the net torque about the origin. This implies that angular momentum is a conserved quantity as long as there is no net torque applied to the particle. What's more, this conservation can be generalized to a system of particles under most conditions so that:

$$\mathbf{L}_{\text{system}} = \text{constant} \Leftrightarrow \sum \tau_{\text{external}} = 0$$

where **Ä**external is any torque applied to the system of particles.

The conservation of angular momentum is used extensively in analyzing what is called *central force motion*. In central force motion, two bodies form an isolated system not influenced by outside forces, and the origin is placed somewhere on the line between the two bodies. Since any force the bodies exert on each other must be directed along this line, there can be no net torque, with respect to the afore-mentioned origin, on either body. Thus, angular momentum is conserved. Constant angular momentum is extremely useful when dealing with the orbits of planets and satellites, and also when analyzing the Bohr model of the atom.

In modern (late 20th century) theoretical physics, angular momentum is described using an different formalism. Under this formalism, angular momentum is the 2-form Noether charge associated with rotational invariance (As a result, angular momentum isn't defined for general curved spacetimes, unless it happens to be asymptotically rotationally invariant). For a system of point particles without any intrinsic angular momentum, it turns out to be

$$\sum_i \mathbf{r} \wedge \mathbf{p}$$

(Here, the wedge product is used.).

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Spin

Spin is an intrinsic angular momentum associated with quantum mechanical particles. Unlike classical "spinning" objects, which derive their angular momentum from the rotation of their constituent parts, spin angular momentum is not associated with any rotating internal masses. For example, elementary particles, such as the electron, possess spin angular momentum, even though they are point particles. Also, unlike classical mechanical spinning, the spin is not described by a vector, but by a two-component object (for spin-1/2 particles): there is an observable difference in how it transforms under coordinate rotations.

Other subatomic particles, such as neutrons, which have zero electrical charge, also possess spin.

When applied to spatial rotations, the principles of quantum mechanics state that the observed values of angular momentum (which are eigenvalues of the angular momentum operator) are restricted to integer or half-integer multiples of $h/2$À. This applies to spin angular momentum as well. Furthermore, the spin-statistics theorem states that particles with integer spin correspond to bosons, and particles with half-integer spin correspond to fermions.

A rotating charged body in an inhomogenous magnetic field will experience a force. Electrons in an inhomogenous magnetic field also experience a force, and this is why people have imagined the electron as "spinning around". The observed forces vary for different electrons, and these differences are attributed to differences in spin. The spin of electrons is therefore typically measured by observing their deflection in an inhomogenous magnetic field. In accordance with the predictions of theory, only half-integer multiples of $h/2$À are ever observed for electrons.

History

Spin was first discovered in the context of the emission spectrum of alkali metals. In 1924, Wolfgang Pauli (who was possibly the most influential physicist in the theory of spin) introduced what he called a "two-valued quantum degree of freedom" associated with the electron in the outermost shell. This allowed him to formulate the Pauli exclusion principle, stating that no two electrons can share the same quantum numbers.

The physical interpretation of Pauli's "degree of freedom" was initially unknown. Ralph Kronig, one of Landé's assistants, suggested in early 1925 that it was produced by the self-rotation of the electron. When Pauli heard about the idea, he criticized it severely, noting that the electron's hypothetical surface would have to be moving faster than the speed of light in order for it to rotate quickly enough to produce the necessary angular momentum. This would violate the theory of relativity. Largely due to Pauli's criticism, Kronig decided not to publish his idea.

In the fall of that year, the same thought came to two young Dutch physicists, George Uhlenbeck and Samuel Goudsmit. Under the advice of Paul Ehrenfest, they published their results in a small paper. It met a favorable response, especially after L.H. Thomas managed to resolve a factor of two discrepancy between experimental results and Uhlenbeck and Goudsmit's calculations (and Kronig's unpublished ones.) This discrepancy was due to the

necessity to take into account the orientation of the electron's tangent frame, in addition to its position; mathematically speaking, a fiber bundle description is needed. The tangent bundle effect is additive and relativistic (i.e. it vanishes if *c* goes to infinity); it is one half of the value obtained without regard for the tangent space orientation, but with opposite sign. Thus the combined effect differs from the latter by a factor two (Thomas precession).

Despite his initial objections to the idea, Pauli formalized the theory of spin in 1927, using the modern theory of quantum mechanics discovered by Schrödinger and Heisenberg. He pioneered the use of Pauli matrices as a representation of the spin operators, and introduced a two-component spinor wave-function.

Pauli's theory of spin was non-relativistic. However, in 1928, Paul Dirac published the Dirac equation, which described the relativistic electron. In the Dirac equation, a four-component spinor (known as a "Dirac spinor") was used for the electron wave-function.

In 1940, Pauli proved the spin-statistics theorem, which states that fermions have half-integer spin and bosons integer spin.

Application

A possible application of spin is as a binary information carrier in spin transistors. Electronics based on spin transistors is called spintronics.

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Dimension

Dimension (from Latin "measured out") is, in essence, the number of degrees of freedom available for movement in a space. (In common usage, the dimensions of an object are the measurements that define its shape and size. That usage is related to, but different from, what this article is about.)

For example, the space in which we live appears to be 3-dimensional. We can move up, north or west, and movement in any other direction can be expressed in terms of just these three. Moving down is the same as moving up a negative amount. Moving northwest is merely a combination of moving north and moving west.

Some theories predict that the space we live in has in fact many more dimensions (frequently 10, 11 or 26) but that the universe measured along these additional dimensions is subatomic in size. See string theory.

Time is frequently referred to as the "fourth dimension"; time is not the fourth dimension of space, but rather of spacetime. This does not have a Euclidean geometry, so temporal directions are not entirely equivalent to spatial dimensions. A tesseract is an example of a four-dimensional object.

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Time

One can say that one event occurs *after* another event. Furthermore one can measure *how much* one event occurs *after* another. The answer to *how much* is the amount of **time** between the those two events.

One way of defining the idea of 'after' is based on the assumption of causality. The work humanity has done to increasingly understand the nature and measurement of time, through the work of making and improving calendars and clocks, has been a major engine of scientific discovery.

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Measurement of time

The standard unit for time is the SI second, from which larger units are defined like the minute, hour, day, week, month, year, decade, and century. Time can be measured, just like other physical dimensions. Measuring devices for time are clocks. Very accurate clocks are often called chronometers. The best available clocks are atomic clocks.

There are several continuous time scales in current use: Universal Time, International Atomic Time (TAI), which is the basis for other time scales, Coordinated Universal Time (UTC), which is the standard for civil time, Terrestrial Time (TT), etc. Mankind has invented calendars to track the passages of days, weeks, months, and years.

Time in engineering and applied physics

In physics, time is defined as the distance between events along the fourth axis of the spacetime manifold. Special relativity showed that time cannot be understood except as part of spacetime, a combination of space and time. The distance between events now depends on the relative speed of the observers of the events. General relativity further changed the notion of time by introducing the idea of curved spacetime. An important unit of time in theoretical physics is the **Planck time** – see Planck units for more details.

Time in philosophy and theoretical physics

Important questions in the philosophy of time include: Is time absolute or merely relational? Is time without change conceptually impossible or is there more to the idea? Does time "pass" or are the ideas of past, present and future entirely subjective, descriptions only of our deception by the senses?

Zeno's paradoxes fundamentally challenged the ancient conception of time, and thereby helped motivate the development of the calculus. A point of contention between Newton and Leibniz concerned the question of absolute time: the former believed time was, like space, a container for events, while the latter believed time was, like space, a conceptual apparatus describing the interrelations between events. McTaggart believed, rather eccentrically and on the basis of a very shaky argument, that time and change are illusions. Parmenides (of whom Zeno was a follower) held a similar belief based on a similarly shaky, but rather more interesting argument.

Einstein's theory of relativity linked time and space into spacetime in a way that also had philosophical consequences, making the idea of block time more credible, and thus affecting ideas of free will and causality.

The engineer J. W. Dunne developed a theory of time whereby he considered our perception of time like notes being played on piano. Having had a number of prescient dreams, he monitored his dreams and found that they generally included as many past as future events. From this he concluded that in dreams we escape linear time. He published his ideas in *An Experiment with Time* in 1927 and followed this with other books.

Perception of time

One may perceive time to go fast ("time flies"), meaning that a duration seems less than it is;

this may be considered an advantage:

- in the case of something of fixed duration which is relatively unpleasant, which may be e.g.:
  - work (perhaps not as pleasant as leisure time, but done for the money)
  - travel (if not done for its own sake, but to get somewhere)
  - waiting, boredom

it may be considered a disadvantage:

- in the case of something of fixed duration which is relatively pleasant, which may be e.g.:
  - leisure time, holidays

(on the other hand, that the time has flown is considered a sign that it has been enjoyable)

- if one has a lot to do
- on a larger time scale, "getting old quickly"

Time also seems to go fast when sleeping, some of the above applies, e.g. it may be an advantage to sleep as train or car passenger, and sleep long in the case of boredom, while it may be wasteful to sleep long on holidays.

Books

- Einstein's Clocks and Poincaré's Maps: Empires of Time. By Peter Galison. W.W. Norton; 256 pages

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Space

The definition of **space** in physics is contentious. Various concepts used to try to define space have included:

- the structure defined by the set of "spatial relationships" between objects
- a manifold defined by a coordinate system where an object can be located.
- the entity that stops all objects in the universe from touching one another

In classical physics, space is a three-dimensional Euclidean space where any position can be described using three coordinates. Relativistic physics examines spacetime rather than space; spacetime is modeled as a four-dimensional manifold.

Philosophical questions concerning space include: Is space absolute or purely relational? Does space have one correct geometry, or is the geometry of space just a convention? Historical Eminences who have taken sides in these debates include Isaac Newton (space is absolute), Gottfried Leibniz (space is relational), and Henri Poincaré (spatial geometry is a convention).

Two important thought-experiments connected with these questions are: Newton's bucket argument and Poincaré's disc-world.

See also: Philosophy of physics

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Spacetime

In special relativity and general relativity, time and three-dimensional space are treated together as a single four-dimensional manifold called **spacetime** (alternatively, **space-time**; see below). A point in spacetime may be referred to as an **event**. Each event has four coordinates (t, x, y, z).

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Reference frame

Just as the x, y, z coordinates of a point depend on the axes one is using, so distances and time intervals, invariant in Newtonian physics, may depend on the reference frame of an observer, in relativistic physics. See length contraction and time dilation. This is the central lesson of special relativity.

The central lesson of general relativity is that spacetime cannot be a fixed background, but is rather a network of evolving relationships.

A **spacetime interval** between two events is the frame-invariant quantity analogous to distance in Euclidean space. The spacetime interval *s* along a curve is defined by

$$ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$$

where *c* is the speed of light (some people flip the signs of the equation). A basic assumption of relativity is that coordinate transformations have to leave intervals invariant. Intervals are invariant under Lorentz transformations.

The spacetime intervals on a manifold define a pseudo-metric called the Lorentz metric. This metric is very similar to distance in Euclidean space. However, note that whereas distances are always positive, intervals may be positive, zero, or negative. Events with a spacetime interval of zero are separated by the propagation of a light signal. Events with a positive spacetime interval are in each other's future or past, and the value of the interval defines the proper time measured by an observer travelling between them. Spacetime together with this pseudo-metric makes up a pseudo-Riemannian manifold.

One of the simplest interesting examples of a spacetime is R^4 with the spacetime interval defined above. This is known as Minkowski space, and is the usual geometric setting for Special Relativity. In contrast, General Relativity says that the underlying manifold will not be flat, if gravity is present, and thus it calls for the use of spacetime rather than Minkowski space.

Strictly speaking one can also consider events in Newtonian physics as a single spacetime. This is Galilean-Newtonian relativity, and the coordinate systems are related by Galilean transformations. However, since these preserve spatial and temporal distances independently, such a spacetime can be decomposed unarbitrarily, which is not possible in the general case.

Some general facts about spacetimes

A compact manifold can be turned into a spacetime if and only if its Euler characteristic is 0.

Any non-compact 4-manifold can be turned into a spacetime.

Many spacetimes have physical interpretations which most physicists would consider bizarre or unsettling. For example, a compact spacetime has closed timelike curves, which violate our usual ideas of causality. For this reason, mathematical physicists usually consider only restricted subsets of all the possible spacetimes. One way to do this is to study "realistic" solutions of the equations of General Relativity. Another way is add some additional "physically reasonable" but still fairly general geometric restrictions, and try to prove interesting things about the resulting spacetimes. The latter approach has lead to some important results, most notably the Penrose-Hawking singularity theorems.

In mathematical physics it is also usual to restrict the manifold to be connected and Hausdorff. A Hausdorff spacetime is always paracompact.

Is Spacetime Quantized?

Current research is focused on the nature of spacetime at the Planck scale. Loop quantum gravity, string theory, and black hole thermodynamics all predict a quantized spacetime with agreement on the order of magnitude. Loop quantum gravity even makes precise predictions about the geometry of spacetime at the Planck scale.

Space-time vs. Spacetime

Examples of use of *spacetime*:

- D. J. Griffiths' *Introduction to Electrodynamics* (Upper Saddle River, N. J.: Prentice-Hall, 1989)
- numerous books with *spacetime* in title
  - E. F. Taylor and J. A. Wheeler, *Spacetime Physics* (San Francisco: W. H. Freeman, 1966)
- Caltech class: "Spacetime 101"
- .edu matches online are almost exclusively for *spacetime*

Examples of use of *space-time*:

- Brehm & Mullin, *Introduction to the Structure of Matter* (ISBN 047160531X)
- Hawking & Ellis, *The large-scale structure of space-time* (ISBN 0521099064)

Related concepts

Gravity

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Length

In general English usage, **length** is but one particular instance of distance – an object's **length** is how *long* the object is – but in the physical sciences and engineering, the word ***length*** is in some contexts used synonymously with "distance". **Height** is the term for vertical length, **width** is a lateral distance; an object's width is less than its length. No one speaks of "the length from here to Alpha centauri", but rather of "the distance from here to Alpha centauri," but when one speaks of distance more abstractly, one says "A mile, or a kilometer, is a unit of **length**" or "...of distance", and the two statements are synonymous. Likewise, a mountain might be a mile in height. Length is the metric of one dimension of space. The metric of space itself is volume, or $(\text{length})^3$. Length is commonly considered to be one of the fundamental units, meaning that it cannot be defined in terms of other dimensions. However, a set of units can be constructed where length is dimensionless – see Planck units.

Length is not an intrinsic property of anything, however, in that two observers can measure the same "thing" (i.e. distance between events, length of a board) and come up with a different answer. This strange property of space is explained by Albert Einstein's special theory of relativity.

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Velocity

Velocity is a vector measurement of the rate and direction of motion. The scalar absolute value (magnitude) of velocity is speed. Velocity can also be defined as rate of change of displacement.

In both mechanics the average speed v of an object moving a distance d during a time interval t is described by the simple formula:

$$v = d/t.$$

The instantaneous velocity vector $\mathbf{v}$ of an object whose position at time t is given by $\mathbf{x}(t)$ can be computed as the derivative

$$\mathbf{v} = \mathrm{d}\mathbf{x}/\mathrm{d}t.$$

Acceleration is the change of an object's velocity over time. The average acceleration of a of an object whose speed changes from v_i to v_f during a time interval t is given by:

$$a = (v_f - v_i)/t.$$

The instantaneous acceleration vector $\mathbf{a}$ of an object whose position at time t is given by $\mathbf{x}(t)$ is

$$\mathbf{a} = \mathrm{d}^2\mathbf{x}/(\mathrm{d}t)^2$$

The final velocity v_f of an object which starts with velocity v_i and then accelerates at constant acceleration a for a period of time t is:

$$v_f = v_i + at$$

The average velocity of an object undergoing constant acceleration is $(v_f + v_i)/2$. To find the displacement d of such an accelerating object during a time interval t, substitute this expression into the first formula to get:

$$d = t(v_f + v_i)/2$$

When only the object's initial velocity is known, the expression

$$d = v_i t + (a't^2)/2$$

can be used. These basic equations for final velocity and displacement can be combined to form an equation that is independent of time:

$$v_f^2 = v_i^2 + 2ad$$

The above equations are valid for both classical mechanics and special relativity. Where classical mechanics and special relativity differ is in how different observers would describe the same situation. In particular, in classical mechanics, all observers agree on the value of 't' and the transformation rules for position create a situation in which all non-accelerating observers would describe the acceleration of an object with the same values. Neither is true for special relativity.

The kinetic energy (movement energy) of a moving object is linear with both its mass and the square of its velocity:

$$E_v = \frac{1}{2}mv^2$$

The kinetic energy is a scalar quantity.

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Force

Force isn't really a fundamental quantity in physics, despite the inertia of physics education still introducing students to physics via the Newtonian concept of force. More fundamental are momenta, energy and stress. In fact, no one measures force directly. Instead, everytime one says one is measuring a force, a quick rethinking would make one realize that what one really measures is stress (or maybe its gradient). The "force" you feel on your skin, for example, is really your pressure nerve cells picking up a change in pressure. A spring meter measures the tension of the spring, which is really its stress, etc. etc.

In physics, a net **force** acting on a body causes that body to accelerate (i.e. to change its velocity). Force is a vector. The SI unit used to measure force is the newton.

See also engineering mechanics:

- Statics Where the sum of the forces acting on a body in static equilibrium (motionless, Acceleration=0) is zero. F=MA=0
- Dynamics The sum of the forces acting on a body or system over time is non zero with a resulting set of accelerations defined by detailed analysis of equations derived from F=MA.

Force was first described by Archimedes. The total (Newtonian) force on a point particle at a certain instant in a specified situation is defined as the rate of change of its momentum:

$$\mathbf{F} = \lim_{T\to 0} \frac{m\mathbf{v} - m\mathbf{v}_0}{T}$$

Where m is the inertial mass of the particle, v_0 is its initial velocity, v is its final velocity, and T is the time from the initial state to the final state; the expression on the right of the equation being the limit as T goes to zero.

Force was so defined in order that its reification would explain the effects of superimposing situations: If in one situation, a force is experienced by a particle, and if in another situation another force is experience by that particle, then in a third situation, which (according to standard physical practice) is taken to be a combination of the two individual situations, the force experienced by the particle will be the vector sum of the individual forces experienced in the first two situations. This superposition of forces, along with the definition of inertial frames and inertial mass, are the empirical content of Newton's laws of motion.

Since force is a vector it can be resolved into components. For example, a 2D force acting in the direction North-East can be split in to two forces along the North and East directions respectively. The vector-sum of these component forces is equal to the original force.

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More depth

The content of above definition of force can be further explicated. First, the mass of a body times its velocity is designated its momentum (labeled **p**). So the above definition can be written:

$$\mathbf{F} = \frac{\Delta \mathbf{p}}{\Delta t}$$

If **F** is not constant over ”t, then this is the definition of average force over the time interval. To apply it at an instant we apply an idea from Calculus. Graphing **p** as a function of time, the average force will be the slope of the line connecting the momentum at two times. Taking the limit as the two times get closer together gives the slope at an instant, which is called the derivative:

$$\mathbf{F} = \frac{d\mathbf{p}}{dt}$$

With many forces a potential energy field is associated. For instance, the gravitational force acting upon a body can be seen as the action of the gravitational field that is present at the body's location. The potential field is defined as that field whose gradient is minus the force produced at every point:

$$\mathbf{F} = -\nabla U$$

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While force is the name of the derivative of momentum with respect to time, the derivative of force with respect to time is sometimes called yank. Higher order derivates can be considered, but they lack names, because they are not commonly used.

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In most expositions of mechanics, force is usually defined only implicitly, in terms of the equations that work with it. Some physicists, philosophers and mathematicians, such as Ernst Mach, Clifford Truesdell and Walter Noll, have found this problematic and sought a more explicit definition of force.

Relationships between force units and mass units

In the relationship

$$F = m \times a,$$

which is derived from Newton's second law of motion, F is the force in newtons, m the mass in kilograms and a the acceleration in meters per second squared. To a physicist, the kilogram is a unit of mass, but in common usage "kilogram" is a shorthand for "the weight of a one kilogram mass at sea level on earth". At sea level on earth, the acceleration due to gravity (a in the above equation) is 9.807 meters per second squared, so the weight of one kilogram is 1 kg × 9.807 m/s^2 = 9.807 N.

To distinguish these two meanings of "kilogram", the abbreviations "kgm" for kilogram mass (i.e. 1 kg) and "kgf" for kilogram force, also called kilopond (kp), equal to 9.807 N, are sometimes used. These are only informal terms and are not recognized in the SI system of units.

Imperial units of force

The relationship F = m×a mentioned above may also be used with non-metric units.

For example, in imperial engineering units, F is in "pounds force" or "lbf", m is in "pounds mass" or "lbm", and a is in feet per second squared.

As with the kilogram, the pound is colloquially used as both a unit of mass and a unit of force or weight. 1 lbf is the force required to accelerate 1 lbm at 32.174 ft per second squared, since 32.174 ft per second squared is the acceleration due to terrestrial gravity at sea level.

Another imperial unit of mass is the slug, defined as 32.174 lbm. It is the mass that accelerates by one foot per second squared when a force of one lbf is exerted on it.

Conversion between SI and imperial units of force

At sea level on earth, the magnitude of lbm exactly equals the magnitude of lbf, and the magnitude of kgm exactly equals the magnitude of kgf. This equivalency is only true at the surface of the earth, and does not hold up when acceleration other than that of the standard acceleration of gravity (that at the sea level of Earth) is used.

In other words, your mass and force exerted on the ground equal the same number in pounds (that is, lbm and lbf) on Earth at sea level. Since kgf and lbf are units of force, they are invariant, and the equivalence 1 kgf = 2.2046 lbf is always true. However, the conversion 1 kgm = 2.2046 lbm is true only on Earth at sea level.

The concept of weight, unlike force and mass, depends on the environment in which the weighing is done. It can be assumed that this is at sea level on Earth, unless other conditions are stated. Thus one pound mass (lbm) weighs one pound (lbf), and one kilogram mass (kgm) weighs one kilogram force (kgf). Further, an item with a weight of 10 lbf has a mass of 10 lbm and also a mass of 0.3108 slugs (= 10 lbm divided by 31.174 lbm per slug).

By analogy with the slug, there is a rarely used unit of mass called the "metric slug". This is the mass that accelerates at one metre per second squared when pushed by a force of one kgf. An item with a weight (on Earth at sea level) of 10 kgf has a mass of 10 kgm and also a mass of 1.0197 metric slugs (= 10 kgm divided by 9.807 kgm per metric slug).

An even rarer unit of force called the "imperial newton" is defined as the force that accelerates 1 lbm at 1 foot per second squared. Given that 1 lbf = 32.174 lbm times one foot per square second, we have (1/32.174 =) 0.0311 lbf = 1 lbm times 1 foot per square second = 1 imperial newton. Thus 1 lbf = 32.174 imperial newtons.

In conclusion, we have the following conversions, with “metric slugs” used very infrequently, and “imperial newtons” virtually never used.

1 kgf = 9.807 newton 1 metric slug = 9.807 kgm

1 lbf = 32.174 imperial newtons 1 slug = 32.174 lbm

1 kgf = 2.2046 lbf

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Torque

The concept of **torque** in physics originated with the work of Archimedes on levers. Informally, torque can be thought of as "rotational force". The weight that rests on a lever, multiplied by its distance from the lever's fulcrum, is the torque. For example, a weight of three newtons resting two metres from the fulcrum exerts the same torque as one newton resting six metres from the fulcrum. This assumes the force is in a direction at right angles to a straight lever. More generally, one may define torque as the cross product:

$$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$$

where **r** is the vector from the axis of rotation to the point on which the force is acting, and **F** is the vector of force. Torque is important in the design of machines such as engines.

Torque has dimensions of distance × force; the same as energy. However, the units of torque are usually stated as "newton metres" or "foot pounds" rather than joules. Of course this is not simply a coincidence - a torque of 1 Nm applied through a full revolution will

require an energy of exactly 2À J — mathematically, *E* = *Ä* ¸, where *E* is the energy and ¸ is the angle moved, in radians.

A very useful special case, often given as the definition of torque in fields other than physics, is as follows:

Ä = moment arm × force

The construction of the "moment arm" is shown in the figure below, along with the vectors **r** and **F** mentioned above. The problem with this definition is that it does not give the direction of the torque, and hence it is difficult to use in three dimensional cases. Note that if the force is perpendicular to the displacement vector **r**, the moment arm will be equal to the distance to the centre, and torque will be a maximum. This gives rise to the approximation

Ä = distance to centre × force

For example, if a person places a force of 9.8 N (1 kg) on a spanner which is 0.5 m long, the torque will be approximately 4.9 Nm, assuming that the person pulls the spanner in the direction best suited to turning bolts.

Torque is the time-derivative of angular momentum, just as force is the time derivative of linear momentum. For multiple torques acting simultaneously:

$$\sum \boldsymbol{\tau} = \frac{d\mathbf{L}}{dt}$$

where **L** is angular momentum. See also proof of angular momentum.

Torque on a rigid body can be written in terms of rotational inertia I: **L** = I**É** so if I is constant,

$$\boldsymbol{\tau} = I\frac{d\boldsymbol{\omega}}{dt} = I\boldsymbol{\alpha}$$

where **±** is angular acceleration, a quantity usually measured in rad/s^2.

The measurement of torque is important in automotive engineering, being concerned with the transmission of power from the drive train to the wheels of a vehicle. It is also used where the tightness of screws and bolts is crucial (see torque wrench). Torque is also the easiest way to explain mechanical advantage in just about every simple machine except the pulley.

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Wave

A **wave** is a disturbance that propagates. Apart from electromagnetic radiation, and probably gravitational radiation, which can travel through vacuum, waves have a medium (which on deformation is capable of producing elastic restoring forces) through which they travel and can transfer energy from one place to another without any of the particles of the medium being displaced permanently; i.e. there is no associated mass transport. Instead, any particular point oscillates around a fixed position.

A medium is called:

1. **linear** if different waves at any particular point in the medium can be added,
2. **bounded** if it is finite in extent,otherwise **unbounded**.
3. **uniform** if its physical properties are unchanged at different points,
4. **isotropic** if its physical properties are **same** in different directions.

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Examples of waves

- Sea-waves, which are perturbations that propagate through water (see also surfing and tsunami).
- Sound - a mechanical wave that propagates through air, liquid or solids, and is of a frequency detected by the auditory system. Similar are seismic waves in earthquakes, of which there are the S, P and L kinds.
- Light, radio waves, x-rays, etc. make up electromagnetic radiation. In this case propagation is possible without a medium, through vacuum.

Characteristic properties

All waves have common behaviour under a number of standard situations. All waves can experience the following:

- Reflection - when a wave turns back from the direction it was travelling, due to hitting a reflective material.
- Refraction - the change of direction of waves due to them entering a new medium.
- Diffraction - the spreading out of waves, for example when they travel through a small slit.
- Interference - the addition of two waves that come in to contact with each other.
- Dispersion - the splitting up of a wave up depending on frequency.

Transverse and longitudinal waves

Transverse waves are those with vibrations perpendicular to the wave's direction of travel; examples include waves on a string and electromagnetic waves. Longitudinal waves are those with vibrations along the wave's direction of travel; examples include sound waves.

Ripples on the surface of a pond are actually a combination of transverse and longitudinal waves; therefore, the points on the surface follow elliptical paths.

Polarization

Transverse waves can be polarized. Unpolarised waves can oscillate in any direction in the plane perpendicular to the direction of travel, while polarized waves oscillate in only one direction perpendicular to the line of travel.

Physical description of a wave

Waves can be described using a number of standard variables including: frequency, wavelength, amplitude and period. The amplitude of a wave is the measure of the magnitude of the maximum disturbance in the medium during one wave cycle, and is measured in units depending on the type of wave. For examples, waves on a string have an amplitude expressed as a distance (meters), sound waves as pressure (pascals) and electromagnetic waves as the amplitude of the electric field (volts/meter). The amplitude may be constant (in which case the wave is a *c.w.* or *continuous wave*) or may vary with time and/or position. The form of the variation of amplitude is called the *envelope* of the wave.

The period (T) is the time for one complete cycle for an oscillation of a wave. The frequency (F) is how many periods per unit time (for example one second) and is measured in hertz. These are related by:

$$f = \frac{1}{T}.$$

When waves are expressed mathematically, the *angular frequency* (*É*, radians/second) is often used; it is related to the frequency *f* by:

$$f = \frac{\omega}{2\pi}.$$

Travelling waves

Waves that remain in one place are called *standing waves* - eg vibrations on a violin string. Waves that are moving are called *travelling waves*, and have a disturbance that varies both with time *t* and distance *z*. This can be expressed mathematically as:

y = *A*(*z*,*t*)cos(É*t* - *kz* + Æ),

where *A*(*z*,*t*) is the amplitude envelope of the wave, *k* is the *wave number* and *Æ* is the *phase*. The velocity *v* of this wave is given by:

$$v = \frac{\omega}{k} = \lambda f,$$

where *»* is the *wavelength* of the wave.

The wave equation

In the most general sense, not all waves are sinusoidal. One example of a non-sinusoidal wave is a pulse that travels down a rope resting on the ground. In the most general case, any function of x, y, z, and t that is a non-trivial solution to the wave equation is a wave. The wave equation is a differential equation which describes a harmonic wave passing through a certain medium. The equation has different forms depending on how the wave is transmitted, and on what medium. A non-linear wave-equation can cause mass transport.

The Schrödinger equation describes the wave-like behaviour of particles in quantum mechanics. Solutions of this equation are wave functions which can be used to describe the probability density of a particle.

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Wavefunction

A **wavefunction** is a scalar function that describes the properties of waves.

- Boson - Particle with symmetric wavefunction
- Fermion - Particle with antisymmetric wavefunction

See Quantum mechanics

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Quantum entanglement

Quantum entanglement is a quantum mechanical phenomenon in which the quantum states of two or more objects have to be described with reference to each other, even though the individual objects may be spatially separated. This leads to correlations between observable physical properties of the systems that are stronger than any classical correlations. As a result, measurements performed on one system may be interpreted as "influencing" other systems entangled with it. However, no information can be transmitted through entanglement.

Entanglement is one of the properties of quantum mechanics which caused Einstein and others to dislike the theory. In 1935, Einstein, Podolsky, and Rosen formulated the EPR paradox, demonstrating that entanglement makes quantum mechanics a non-local theory. Einstein famously derided entanglement as "spooky action at a distance."

On the other hand, quantum mechanics was highly successful in producing correct experimental predictions, and the phenomenon of "spooky action" could in fact be observed. Some suggested the existence of unknown microscopic parameters, known as "hidden variables", that were deterministic and obeyed the locality principle, but gave rise to quantum mechanical behavior in the bulk. However, in 1964 Bell showed that the effects of quantum entanglement could be experimentally distinguished from the effects of a broad class of local hidden-variable theories. Subsequent experiments verified the quantum mechanical predictions, and entanglement has now become accepted as a *bona fide* physical phenomenon. The "Bell inequalities" are described in greater detail in the article EPR paradox.

Entanglement obeys the letter if not the spirit of relativity. Although two entangled systems can interact across large spatial separations, no useful information can be transmitted in this way, so causality cannot be violated through entanglement. This occurs for two subtle reasons: (i) quantum mechanical measurements yield probabilistic results, and (ii) the no cloning theorem forbids the statistical inspection of entangled quantum states.

Although no information can be transmitted through entanglement alone, it is possible to transmit information using a set of entangled states used in conjunction with a *classical* information channel. This process is known as quantum teleportation. Despite its name, quantum teleportation can not be used to transmit information faster than light, because a classical information channel is involved.

Though an area of active research, some of the essential properties of entanglement are now understood, and it is the basis for emerging technologies such as quantum computing and quantum cryptography. In the following article, we will briefly survey the mathematical formulation of entanglement.

Formalism

The following discussion builds on the theoretical framework developed in the articles bra-ket notation and mathematical formulation of quantum mechanics.

Consider two systems A and B, with respective Hilbert spaces H_A and H_B. The Hilbert space of the composite system is $H_A \times H_B$. If the first system is in state |È*$_A$ and the second in state |Æ*$_B$, the state of the composite system is

$$|\psi\rangle_A\ |\phi\rangle_B.$$

This is called a *pure state*.

Pick observables (and corresponding Hermitian operators) ©$_A$ acting on H_A, and ©$_B$ acting on H_B. According to the spectral theorem, we can find a basis {|i*$_A$} for H_A composed of eigenvectors of ©$_A$, and a basis {|j*$_B$} for H_B composed of eigenvectors of ©$_B$. We can then write the above pure state as

$$\left(\sum_i a_i|i\rangle_A\right)\left(\sum_j b_j|j\rangle_B\right),$$

for some choice of complex coefficients a_i and b_j. This is not the most general state of $H_A \times H_B$, which has the form

$$\sum_{i,j} c_{ij}|i\rangle_A\ |j\rangle_B.$$

If such a state cannot be factored into the form of a separable state, it is known as an *entangled state*.

For example, given two basis vectors {|0*$_A$, |1*$_A$} of H_A and two basis vectors {|0*$_B$, |1*$_B$} of H_B, the following is an entangled state:

$$\frac{1}{\sqrt{2}}\left(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B\right).$$

If the composite system is in this state, neither system A nor system B have a definite state. Instead, their states are superposed with one another. In this sense, the systems are "entangled".

Now suppose Alice is an observer for system A, and Bob is an observer for system B. If Alice performs the measurement ©$_A$, there are two possible outcomes, occurring with equal probability:

1. Alice measures 0, and the state of the system collapses to |0*$_A$ |1*$_B$
2. Alice measures 1, and the state of the system collapses to |1*$_A$|0*$_B$.

If the former occurs, any subsequent measurement of ©$_B$ performed by Bob always returns 1. If the latter occurs, Bob's measurement always returns 0. Thus, system B has been altered by Alice performing her measurement on system A., even if the systems A and B are spatially separated. This is the foundation of the EPR paradox.

The outcome of Alice's measurement is random. Alice cannot decide which state to collapse the composite system into, and therefore cannot transmit information to Bob by acting on her system. (There is a possible loophole: if Bob could make multiple duplicate copies of the state he receives, he could obtain information by collecting statistics. This loophole is closed by the no cloning theorem, which forbids the creation of duplicate states.) Causality is thus preserved, as we claimed above.

Entropy

Quantifying entanglement is an important step towards better understanding the phenomenon. The method of density matrices provides us with a formal measure of

entanglement. Let the state of the composite system be |¨*. The projection operator for this state is denoted

$$\rho_T = |\Psi\rangle\, \langle\Psi|\,.$$

We define the density matrix of system A, a linear operator in the Hilbert space of system A, as the trace of Á$_{T}$ over the basis of system B:

$$\rho_A \equiv \sum_j \langle j|_B \left(|\Psi\rangle\langle\Psi|\right) |j\rangle_B = \mathrm{Tr}_B\; \rho_T\,.$$

For example, the density matrix of A for the entangled state discussed above is

$$\rho_A = (1/2)\;(\;|0\rangle_A\langle 0|_A + |1\rangle_A\langle 1|_A\;)$$

and the density matrix of A for the pure state discussed above is

$$\rho_A = |\psi\rangle_A\langle\psi|_A\,.$$

This is simply the projection operator of |È*$_{A}$. Note that the density matrix of the composite system, Á$_{T}$, also takes this form. This is unsurprising, since we assumed that the state of the composite system is pure.

Given a general density matrix Á, we can calculate the quantity

$$S = -k\mathrm{Tr}\left(\rho \ln \rho\right)$$

where *k* is Boltzmann's constant, and the trace is taken over the space *H* in which Á acts. It turns out that S is precisely the entropy of the system corresponding to *H*.

The entropy of any pure state is zero, which is unsurprising since there is no uncertainty about the state of the system. The entropy of any of the two subsystems of the entangled state discussed above is *k*ln 2 (which can be shown to be the maximum entropy for a one-level system). If the overall system is pure, the entropy of its subsystems can be used to measure its degree of entanglement with the other subsystems.

It can also be shown that unitary operators acting on a state (such as the time evolution operator obtained from the Schrödinger equation) leave the entropy unchanged. This associates the reversibility of a process with its resulting entropy change, which is a deep result linking quantum mechanics to information theory and thermodynamics.

Ensembles

The language of density matrices is also used to describe quantum ensembles, or a collection of identical quantum systems.

Consider a "black-box" apparatus that spits electrons towards an observer. The electrons' Hilbert spaces are identical. The apparatus might produce electrons that are all in the same state; in this case, the electrons received by the observer are then called a *pure ensemble*.

However, the apparatus could produce electrons in different states. For example, it could produce two populations of electrons: one with state |**z**+* (spins aligned in the positive **z** direction), and the other with state |**y**-* (spins aligned in the negative **y** direction.) Generally, there can be any number of populations, each corresponding to a different state. This is a *mixed ensemble*.

We can describe an ensemble as a collection of populations with weights w_i and corresponding states |±$_{i}$*. The density matrix of the ensemble is defined as

$$\rho = \sum_i w_i |\alpha_i\rangle\langle\alpha_i|$$.

All the above results for density matrices and the quantum entropy remain valid with this definition. Motivated by this, as well as the many-worlds interpretation, many physicists now believe that *all* mixed ensembles can be explained as entangled quantum states.

The vacuum in quantum field theory, is hugely entangled, so entanglement isn't just about particles. See also Reeh-Schlieder theorem.

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Harmonic oscillator

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Introduction

A **harmonic oscillator** is any physical system that varies above and below its mean value with a characteristic frequency, *f*. Common examples of harmonic oscillators include pendulums, masses on springs, and RLC circuits.

The following article discusses the harmonic oscillator in terms of classical mechanics. See the article quantum harmonic oscillator for a discussion of the harmonic oscillator in quantum mechanics.

Full Mathematical Definition

Most harmonic oscillators, at least approximately, solve the differential equation:

$$\frac{d^2x}{dt^2} - b\frac{dx}{dt} + {\omega_0}^2 x = A_0 \cos(\omega t)$$

where t is time, b is the damping constant, É$_0$ is the characteristic angular frequency, and A_0cos(Ét) represents something driving the system with amplitude A_0 and angular frequency É. x is the measurement that is oscillating; it can be position, current, or nearly anything else. The angular frequency is related to the frequency, f, by:

$$f = \frac{\omega}{2\pi}$$

Simple Harmonic Oscillator

A simple harmonic oscillator is simply an oscillator that is neither damped nor driven. So the equation to describe one is:

$$\frac{d^2x}{dt^2} + {\omega_0}^2 x = 0$$

Physically, the above never actually exists, since there will always be friction or some other resistance, but two approximate examples are a mass on a spring and an LC circuit.

In the case of a mass hanging on a spring, Newton's Laws, combined with Hooke's law for the behavior of a spring, states that:

$$- ky = ma$$

where k is the spring constant, m is the mass, y is the position of the mass, and a is its acceleration. Rewriting the equation, we obtain:

$$\frac{d^2y}{dt^2} = -\frac{k}{m}y$$

The easiest way to solve the above equation is to recognize that when d^2z/dt^2 -z, z is some form of sine. So we try the solution:

y = *A*cos(É*t* + ´)

$$\frac{d^2y}{dt^2} = -A\omega^2 \cos(\omega t + \delta)$$

where *A* is the amplitude, ´ is the phase shift, and É is the angular frequency. Substituting, we have:

$$-A\omega^2 \cos(\omega t + \delta) = -\frac{k}{m} A \cos(\omega t + \delta)$$

and thus (dividing both sides by -*A* cos(É*t* + ´)):

$$\omega = \sqrt{\frac{k}{m}}$$

The above formula reveals that the angular frequency of the solution is only dependent upon the physical characteristics of the system, and not the initial conditions (those are represented by *A* and ´). That means that what was labelled É is in fact É$_o$. This will become important later.

Driven Harmonic Oscillator

Satisfies equation:

$$\frac{d^2x}{dt^2} + {\omega_0}^2 x = A_0 \cos(\omega t)$$

Good example:

AC LC circuit.

a few notes about what the response of the circuit to different AC frequencies.

Damped Harmonic Oscillator

Satisfies equation:

$$\frac{d^2x}{dt^2} - b\frac{dx}{dt} + {\omega_0}^2 x = 0$$

good example:
weighted spring underwater
Note well: underdamped, critically damped

Damped, Driven Harmonic Oscillator

equation:

$$\frac{d^2x}{dt^2} - b\frac{dx}{dt} + {\omega_0}^2 x = A_0 \cos(\omega t)$$

example:
RLC circuit
Notes for above apply, transient vs steady state response, and quality factor.

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Magnetism

In physics, **magnetism** is a phenomenon by which materials exert an attractive or repulsive force on other materials. Magnetism arises whenever electrically charged particles are in motion. Some well known materials that exhibit magnetic properties are iron, some steels, and the mineral lodestone. All materials are influenced to one degree or another by the presence of a magnetic field, although in some cases the influence is too small to detect without special equipment.

Magnetic forces are fundamental forces that arise due to the movement of electrically charged particles. Maxwell's equations describe the origin and behavior of the fields that govern these forces (see also Biot-Savart's Law).

For the case of electric current moving through a wire, the resulting field is directed according to the "right hand rule". If the right hand is used as a model, and the thumb of the right hand points along the wire from positive towards the negative side, then the magnetic field will wrap around the wire in the direction indicated by the fingers of the right hand. If a loop is formed, such that the charged particles are traveling in a circle, then all of the field lines in the center of the loop are directed in the same direction. The result is called a **magnetic dipole**. When placed in a magnetic field, a magnetic dipole will tend to align itself with that field. For the case of a loop, if the fingers of the right hand are directed in the direction of current flow, the thumb will point in the direction corresponding to the North pole of the dipole.

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Units related to magnetism

volt
tesla
gauss
oersted
weber
ampere
maxwell

Magnetic Dipoles

Magnetic dipoles or magnetic moments can often result on the atomic scale due to the movements of electrons. Each electron has magnetic moments that originate from two sources. The first is the orbital motion of the electron around the nucleus. In a sense this motion can be considered as a current loop, resulting in a magnetic moment along its axis of rotation. The second source of electronic magnetic moment is due to a quantum mechanical property called spin.

In an atom the orbital magnetic moments of some electron pairs cancel each other. The same is true for the spin magnetic moments. The overall magnetic moment of the atom is thus the sum of all of the magnetic moments of the individual electrons, accounting for moment cancellation between properly paired electrons. For the case of a completely filled electron shell or subshell, the magnetic moments completely cancel each other out. Thus only atoms with partially filled electron shells have a magnetic moment. The magnetic properties of materials are in large part determined by the nature and magnitude of the atomic magnetic moments.

Several forms of magnetic behavior have been observed including:

- Diamagnetism
- Paramagnetism
  - Molecular magnet
- Ferromagnetism
  - Antiferromagnetism
  - Ferrimagnetism
  - Metamagnetism
- Spin glass

- Superparamagnetism

Highly magnetic stars called magnetars are also believed to exist.

Models of Magnetic Material

Magnetic material may be modelled by a system of *spins* located at positions in a lattice, where the interaction of neighboring spins contributes to the total energy of the system and the states of the spins change according to some non-deterministic (probabalistic) rule (the *dynamics* of the system). In the Ising model spins have only two possible states (*up* and *down*), whereas in the Potts model they may have more than two possible states.

See also

- electromagnetism

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Electricity

In physics, the electromagnetic phenomenon of **electricity** (or **electric charge**) is a conserved property of matter that can be quantified. In this sense, the phrase "quantity of electricity" is used interchangeably with the phrases "charge of electricity" and "quantity of charge." There are two types of electricity or charge: we call one kind of charge positive and the other negative. Through experiment, we find that like-charged objects repel and opposite-charged objects attract one another. The magnitude of the force of attraction or repulsion is given by Coulomb's Law.

The SI unit of electrical charge is the coulomb.

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History

According to Thales of Miletus, writing *circa* 600 BC, electricity was known to the Ancient Greeks, who found that rubbing fur on various substances, such as amber, would cause an electric charge imbalance. The Greeks noted that the charged amber buttons could attract

light objects such as hair, and that if they rubbed the amber for long enough, they could even get a spark to jump.

An object found in Iraq in 1938, dated to about 250 BC and called the Baghdad Battery, resembles an electrochemical cell and is believed by some to have been used for electroplating. There is no "*firm*" documentary evidence to indicate what the object was used for, though there are other anachronistic descriptions of electrical devices on Egyptian walls and in ancient writings.

In 1600 the English scientist William Gilbert returned to the subject in *De Magnete*, and coined the modern Latin word *electricus* from *·»µºÄÁ¿½* (*elektron*), the Greek word for amber, which soon gave rise to the English words *electric* and *electricity*. He was followed in 1660 by Otto von Guericke, who invented an early electrostatic generator. Other European pioneers were Robert Boyle, who stated in 1675 that electric attraction and repulsion can act across a vacuum; Stephen Gray, who in 1729 classified materials as conductors and insulators; and C. F. Du Fay, who first identified the two types of electric charge that would later be called *positive* and *negative*. The Leyden jar, a type of capacitor for storing electric charge in large quantities, was invented at Leyden University by Pieter van Musschenbroek in 1745. William Watson, experimenting with the Leyden jar, discovered in 1747 that a discharge of static electricity was equivalent to an electric current.

In June, 1752, Benjamin Franklin promoted his investigations of electricity and theories through the famous, though extremely dangerous, experiment of flying a kite during a thunderstorm. Following these experiments he invented a lightning rod and established the link between lightning and electricity. If Franklin did fly a kite in a storm, he did not do it the way it is often described (as it would have been dramatic but fatal). It was either Franklin (more frequently) or Ebenezer Kinnersley of Philadelphia (less frequently) who created the convention of positive and negative charge. Franklin's observations aided later scientists such as Michael Faraday, Luigi Galvani, Alessandro Volta, André-Marie Ampère, and Georg Simon Ohm whose work provided the basis for modern electrical technology. The work of Faraday, Volta, Ampere, and Ohm is honored by society, in that fundamental units of electrical measurement are named after them.

Volta worked with chemicals and discovered that chemical reactions could be used to create positively charged anodes and negatively charged cathodes. When a conductor was attached between these, the difference in the electrical potential (also known as voltage) drives a current between them through the conductor. The potential difference between two points is measured in units of volts in recognition of Volta's work.

The late 19th and early 20th century produced such giants of electrical engineering as Samuel Morse, inventor of the telegraph; Alexander Graham Bell, inventor of the telephone; Thomas Edison (inventor of the phonograph, motion pictures and a practical incandescent light bulb) ; George Westinghouse, inventor of the electric locomotive; Charles Steinmetz, inventor of alternating current; and Nikola Tesla, inventor of the induction motor and developer of polyphase systems.

Tesla performed experiments with very high voltages that are the stuff of legend, involving ball lightning and other effects (some have been duplicated or explained; and others which have not). He contribution to the world of electrodynamics the theory of polyphase alternating current electricity, which he used to build the first induction motor, invented in 1882. In May 1885, Westinghouse, then president of the Westinghouse Electric

Company in Pittsburgh, Pennsylvania, bought the rights to Tesla's patents for polyphase alternating-current dynamos. This led to a contest in the so-called court of public opinion as to which system would be adopted as the standard for power transmission (known as the War of Currents), Edison's direct-current system or Westinghouse's alternating-current method.

Edison conducted a spirited public relations campaign which included his promotion of the electric chair as a method of execution. The electric chair ran on Westinghouse's AC; Edison wanted to prove that AC power was capable of killing, and should therefore be viewed by the public as inherently dangerous. This fear, uncertainty and doubt campaign included the electrocution of Topsy the Elephant. AC power transmission was eventually adopted as the standard.

Electric power

Electric power, for most consumers, is generated centrally by utility companies using coal, oil, hydropower, or nuclear power. In 2000, U.S. electric utilities had 600 gigawatts of maximum summer generating capacity including 261 GW from coal, 41 GW from petroleum, 118 GW from natural gas, 92 GW from hydropower and 86 GW from nuclear fuels. Little generating capacity is presently based on renewable sources such as solar power and wind power. Some individuals and communities prefer renewable sources because there is less pollution, and because users of renewable energy sources can sometimes gain a measure of economic independence from the electrical utilities.

Things that are powered by electricity include lamps; computers and the internet; radio and television; refrigeration; air conditioning; traffic signals; electric guitars and other electronic musical instruments; the spark plugs in automobiles.

Today, for residents of most developed countries, 24-hour, on-demand, access to electrical power is taken for granted. People gripe about their electric bill and about electric power monopolies and utility pricing, but by any comparison with pre-industrial standards of living, electricity is still a bargain. Few would want to go back to life without it.

In electrical engineering, the energy in electromagnetic fields is harnessed to perform useful work - either as a method to transmit energy to the appropriate place and then convert it back into a different, useful form of energy (for instance, heat, light, or motion), or by using the presence or level of electricity to convey information.

Today's electrical engineers enjoy the ability to design circuits using pre-manufactured building blocks such as power supplies, resistors, capacitors, semiconductors such as transistors, and integrated circuits. An integrated circuit inside a computer, a microprocessor, performs millions of computations per second.

Electric current

A flow of electric charge is called an electric current. A direct current (DC) is a steady flow; alternating current (AC) is a flow whose time average is zero, but is not zero at all times. That definiation of AC implies that the flow repeatedly changes direction. (Polarity and numerical sign (i.e. negative vs. positive) are additional terms for direction in this sense).

Flows of electric charge can be produced within conductors and cannot exist within insulators. Some electrical devices that use electrical physics are called electronic devices. See electrical conduction for more information about current flow in materials.

Ohm's Law is an important relationship describing the behaviour of electric currents: voltage potential difference = current * resistance, or:

$$V = IR$$

Electrical phenomena in nature

- lightning
- bioelectricity - Many animals are sensitive to electric fields, some (e.g., sharks) more than others (e.g., people). A few, such as the electric eel, generate their own electric fields.
- matter - since atoms and molecules are held together by electric forces.
- the Earth's magnetic field - which is created by electric currents circulating in the planet's core.

Terminology Issues

In addition to its definition by physicists, the word *electricity* has several popular definitions which are contradictory. Rather than using the word *electricity* to refer to the quantity of electric charge, many sources instead say that electricity is the quantity of electromagnetic energy measured in joules or kilowatt-hours. Other sources call the flow of charges within a conductor by the name *electricity* and they measure the quantity of electricity in terms of amperes. Still others call a wide variety of electrical phenomena by the name *electricity*, e.g. bioelectricity, piezoelectricity, triboelectricity, etc. It is advisable to be extremely careful when interpreting texts which use the frequently misused term *electricity* in place of the more accurate terms electric charge, electric current, electrical energy, etc.

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Electromagnetic radiation

Electromagnetic radiation is a combination of oscillating electric and magnetic fields propagating through space and carrying energy from one place to another. Light is a form of electromagnetic radiation. The theoretical study of electromagnetic radiation is called electrodynamics, a subfield of electromagnetism.

Any electric charge which accelerates radiates electromagnetic radiation. When any wire (or other conducting object such as an antenna) conducts alternating current, electromagnetic radiation is propagated at the same frequency as the electric current. Depending on the circumstances, it may behave as waves or as particles. As a wave, it is characterized by a velocity (the velocity of light), wavelength, and frequency. When considered as particles, they are known as photons, and each has an energy related to the frequency of the wave given by Planck's relation **E = hv**, where **E** is the energy of the photon, **h** is Planck's constant - 6.626×10^{-34} J·s - and **v** is the frequency of the wave. Einstein later updated this formula to $\mathbf{E_{photon} = hv}$.

Generally, electromagnetic radiation is classified by wavelength into radio, microwave, infrared light, visible light, ultraviolet light, X-rays and gamma rays. The details of this classification are contained in the article on the electromagnetic spectrum.

The effect of radiation depends on the amount of energy per quantum it carries. High energies correspond to high frequencies and short wavelengths, and vice versa. One rule is always obeyed, regardless of the circumstances. Radiation in vacuum always travels at the speed of light, *relative to the observer*, regardless of the observer's velocity. (This observation led to Albert Einstein's development of the theory of special relativity).

Much information about the physical properties of an object can be obtained from its electromagnetic spectrum; this can be either the spectrum of light emitted from, or transmitted through the object. This involves spectroscopy and is widely used in astrophysics. For example; many hydrogen atoms emit radio waves which have a wavelength of 21.12 cm.

When electromagnetic radiation passes through a conductor it induces an electric current flow in the conductor. This effect is used in antennas. Electromagnetic radiation may also cause certain molecules to oscillate and thus to heat up; this is exploited in microwave ovens.

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Temperature

In physics, **temperature** is the physical property of a system which underlies the common notions of "hot" and "cold"; generally the material with the higher temperature is said to be hotter.

Formally, temperature is that property which governs the transfer of thermal energy, or heat, between one system and another. When two systems are at the same temperature, they are in *thermal equilibrium* and no heat transfer will occur. When a temperature difference

does exist, heat will tend to move from the *higher* temperature system to the *lower* temperature system, until thermal equilibrium is again established. This heat transfer may occur via conduction, convection or radiation (see heat for additional discussion of the various mechanisms of heat transfer). The formal properties of temperature are studied in thermodynamics. Temperature also plays an important role in almost all fields of science, including physics, chemistry, and biology.

Temperature is related to the amount of thermal energy or heat in a system. As more heat is added the temperature rises, similarly a decrease in temperature corresponds to a loss of heat from the system. On the microscopic scale this heat corresponds to the random motion of atoms and molecules in the system. Thus, an increase in temperature corresponds in an increase in the rate of movement of the atoms in the system.

Many physical properties of materials including the phase (gas, liquid or solid), density, solubility, vapor pressure, and electrical conductivity depend on the temperature. Temperature also plays an important role in determining the rate and extent to which chemical reactions occur. This is one reason why the human body has several elaborate mechanisms for maintaining the temperature at 37 °C, since temperatures only a few degrees higher can result in harmful reactions with serious consequences. Temperature also controls the type and quantity of thermal radiation emitted from a surface. One application of this effect is the incandescent light bulb, in which a tungsten filament is electrically heated to a temperature at which significant quantities of visible light are emitted.

Temperature is an intrinsic property of a system, meaning that it does not depend on the system size or the amount of material in the system. Other intrinsic properties include pressure and density. By contrast, mass and volume are extrinsic properties, and depend on the amount of material in the system.

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Units of Temperature

The basic unit of temperature in the International System of Units is the kelvin (K). One kelvin is formally defined as 1/273.16 of the temperature of the triple point of water (the point at which water, ice and water vapor exist in equilibrium). The temperature 0 K is called absolute zero and corresponds to the point at which the molecules and atoms have the least possible thermal energy. An important unit of temperature in theoretical physics is the Planck temperature (1.4×10^{32} K).

For everyday applications, it is often convenient to use the Celsius (previously centigrade) scale, in which 0 °C corresponds to the temperature at which water freezes and 100 °C corresponds to the boiling point of water at sea level. In this scale a temperature difference of 1 degree is the same as a 1 K temperature difference, so the scale is essentially the same as the kelvin scale, but offset by the temperature at which water freezes (273.15 K). Thus the following equation can be used to convert from Celsius to kelvin.

$$T(K) = T(C) + 273.15$$

In the United States, the Fahrenheit scale is widely used. On this scale the freezing point of water corresponds to 32 °F and the boiling point to 212 °F. The following formula can be used to convert between Fahrenheit and Celsius:

$$T(C) = \frac{5}{9} \times (T(F) - 32)$$

Other temperature scales include the Rankine and the Reaumur.

Theoretical foundation of temperature

Zeroth-Law definition of temperature

While most people have a basic understanding of the concept of temperature, its formal definition is rather complicated. Before jumping to a formal definition, let's consider the concept of thermal equilibrium. If two closed systems with fixed volumes are brought together, so that they are in thermal contact, changes may take place in the properties of both systems. These changes are due to the transfer of heat between the systems. When a state is reached in which no further changes occur, the systems are in thermal equilibrium.

Now a basis for the definition of temperature can be obtained from the 'zeroth law of Thermodynamics, which states that if two systems, A and B, are in thermal equilibrium and a third system C is in thermal equilibrium with system A then systems B and C will also be in thermal equilibrium. This is an empirical fact, based on observation rather than theory. Since A, B, and C are all in thermal equilibrium, it is reasonable to say each of these systems shares a common value of some property. We call this property temperature.

Generally, it is not convenient to place any two arbitrary systems in thermal contact to see if they are in thermal equilibrium and thus have the same temperature. Therefore, it is useful to establish a temperature scale based on the properties of some reference system. Then, a measuring device can be calibrated based on the properties of the reference system and used to measure the temperature of other systems. One such reference system is a fixed quantity of gas. Boyle's law indicates that the product of the Pressure and volume (P×V) of a

gas is directly proportional to the temperature. This can be expressed by the Ideal gas law as:

$$PV = nRT \quad (1)$$

where T is temperature, n is the amount of gas (number of moles) and R is the Ideal gas constant. Thus, one can define a scale for temperature based on the corresponding pressure and volume of the gas. In practice, such a **gas thermometer** is not very convenient, but other measuring instruments can be calibrated to this scale.

Equation 1 indicates that for a fixed volume of gas, the pressure increases with increasing temperature. Pressure is just a measure of the force applied by the gas on the walls of the container and is related to the energy of the system. Thus, we can see that an increase in temperature corresponds to an increase in the thermal energy of the system. When two systems of differing temperature are placed in thermal contact, the temperature of the hotter system decreases, indicating that heat is leaving that system, while the cooler system is gaining heat and increasing in temperature. Thus heat always moves from a region of high temperature to a region of lower temperature and it is the temperature difference that drives the heat transfer between the two systems.

Second-Law definition of temperature

In the previous section temperature was defined in terms of the Zeroth Law of thermodynamics. It is also possible to define temperature in terms of the second law of thermodynamics, which deals with entropy. Entropy is a measure of the disorder in a system. The second law states that any process will result in either no change or a net increase in the entropy of the universe. This can be understood in terms of probability. Consider a series of coin tosses. A perfectly ordered system would be one in which every coin toss would come up either heads or tails. For any number of coin tosses, there is only one combination of outcomes corresponding to this situation. On the other hand, there are multiple combinations that can result in disordered or mixed systems, where some fraction are heads and the rest tails. As the number of coin tosses increases, the number of combinations corresponding to imperfectly ordered systems increases. For a very large number of coin tosses, the number of combinations corresponding to ~50% heads and ~50% tails dominates and obtaining an outcome significantly different than 50/50 becomes extremely unlikely. Thus the system naturally progresses to a state of maximum disorder or entropy.

Now, we have stated previously that temperature controls the flow of heat between two systems and we have just shown that the universe, and we would expect any natural system, tends to progress so as to maximize entropy. Thus, we would expect there to be some relationship between temperature and entropy. In order to find this relationship let's first consider the relationship between heat, work and temperature. A Heat engine is a device for converting heat into mechanical work and analysis of the Carnot heat engine provides the necessary relationships we seek. The work from a heat engine corresponds to the difference between the heat put into the system at the high temperature, q_H and the heat ejected at the low temperature, q_C. The efficiency is the work divided by the heat put into the system or:

$$\text{efficiency} = \frac{w_{cy}}{q_H} = \frac{q_H - q_C}{q_H} = 1 - \frac{q_C}{q_H} \quad (2)$$

where w_{cy} is the work done per cycle. We see that the efficiency depends only on q_C/q_H. Because q_C and q_H correspond to heat transfer at the temperatures T_C and T_H, respectively, q_C/q_H should be some function of these temperatures:

$$\frac{q_C}{q_H} = f(T_H, T_C) \quad (3)$$

Carnot's theorem states that all reversible engines operating between the same heat reservoirs are equally efficient. Thus, a heat engine operating between T_1 and T_3 must have the same efficiency as one consisting of two cycles, one between T_1 and T_2, and the second between T_2 and T_3. This can only be the case if:

$$q_{13} = \frac{q_1 q_2}{q_2 q_3}$$

which implies:

$$q_13 = f(T_1,T_3) = f(T_1,T_2)f(T_2,T_3)$$

Since the first function is independent of T_2, this temperature must cancel on the right side, meaning $f(T_1,T_3)$ is of the form $g(T_1)/g(T_3)$ (i.e. $f(T_1,T_3) = f(T_1,T_2)f(T_2,T_3) = g(T_1)/g(T_2)\times g(T_2)/g(T_3) = g(T_1)/g(T_3)$), where g is a function of a single temperature. We can now choose a temperature scale with the property that:

$$\frac{q_C}{q_H} = \frac{T_C}{T_H} \quad (4)$$

Substituting Equation 4 back into Equation 2 gives a relationship for the efficiency in terms of temperature:

$$\text{efficiency} = 1 - \frac{q_C}{q_H} = 1 - \frac{T_C}{T_H} \quad (5)$$

Notice that for T_C=0 K the efficiency is 100% and that efficiency becomes greater than 100% below 0 K. Since an efficiency greater than 100% violates the first law of thermodynamics, this implies that 0 K is the minimum possible temperature. In fact the lowest temperature ever obtained in a macroscopic system was 20 nK, which was achieved in 1995 at NIST. Subtracting the right hand side of Equation 5 from the middle portion and rearranging gives:

$$\frac{q_H}{T_H} - \frac{q_C}{T_C} = 0$$

where the negative sign indicates heat ejected from the system. This relationship suggests the existence of a state function, S, defined by:

$$dS = \frac{dq_{\mathrm{rev}}}{T} \quad (6)$$

where the subscript indicates a reversible process. The change of this state function around any cycle is zero, as is necessary for any state function. This function corresponds to the entropy of the system, which we described previously. We can rearranging Equation 6 to get a new definition for temperature in terms of entropy and heat:

$$T = \frac{dq_{\mathrm{rev}}}{dS} \quad (7)$$

For a system, where entropy S may be a function S(E) of its energy E, the termperature T is given by:

$$\frac{1}{T} = \frac{dS}{dE} \quad (8)$$

The reciprocal of the temperature is the rate of increase of entropy with energy.

Heat capacity

Temperature is related to the amount of thermal energy or heat in a system. As heat is added to the system, the temperature increases by an amount proportional to the amount of heat being added. The constant of proportionality is called the heat capacity and reflects the ability of the material to store heat.

The heat is stored in a variety of modes, corresponding to the various quantum states accessible to the system. As the temperature increases more quantum states become accessible, resulting in an increase in heat capacity. For a monatomic gas at low temperatures, the only accessible modes correspond to the translational motion of the atoms, so all of the energy is due to movement of the atoms (Actually, a small amount of energy, called the Zero Point Energy arises due to the confinement of the gas into a fixed volume, this energy is present even at 0 K). Since the kinetic energy is related to the motion of the atoms, 0 K corresponds to the point at which all atoms are motionless. For such a system, a temperature below 0 K is not possible, since it is not possible for the atoms to move slower than to be motionless.

At higher temperatures, electronic transitions become accessible, further increasing the heat capacity. For most materials these transitions are not important below 10^4 K, however for a few common molecules, such transitions are important even at room temperature. At extremely high temperatures (>10^8 K) nuclear transitions become accessible. In addition to translational, electronic, and nuclear modes, polyatomic molecules also have modes associated with rotation and vibrations along the molecular bonds, which are accessible even at low temperatures. In solids most of the stored heat corresponds to atomic vibrations.

Negative Temperatures

At low temperatures, particles tend to move to their lowest energy states. As you increase the temperature, particles move into higher and higher energy states. As the temperature becomes infinite, the number of particles in the lower energy states and the higher energy states becomes equal. In some situations, it is possible to create a system in which there are more particles in the higher energy states than in the lower ones. This situation can be described with a negative temperature. A negative temperature is not colder than absolute zero, but rather it is hotter than infinite temperature.

The previous section described how heat is stored in the various translational, vibrational, rotational, electronic, and nuclear modes of a system. The macroscopic temperature of a system is related to the total heat stored in all of these modes and in a normal system thermal energy is constantly being exchanged between the various modes. However, for some cases it is possible to isolate one or more of the modes. In practice the isolated modes still exchange energy with the other modes, but the time scale of this exchange is much slower than for the exchanges within the isolated mode. One example is the case of nuclear spins in a strong external magnetic field. In this case energy flows fairly rapidly among the spin states of interacting atoms, but energy transfer between the nuclear spins and other modes is relatively slow. Since the energy flow is predominantly within the

spin system, it makes sense to think of a spin temperature that is distinct from the temperature due to other modes.

Based on Equation 7, we can say a positive temperature corresponds to the condition where entropy increases as thermal energy is added to the system. This is the normal condition in the macroscopic world and is always the case for the translational, vibrational, rotational, and non-spin related electronic and nuclear modes. The reason for this is that there are an infinite number of these types of modes and adding more heat to the system increases the number of modes that are energetically accessible, and thus the entropy. However, for the case of electronic and nuclear spin systems there are only a finite number of modes available (often just 2, corresponding to spin up and spin down). In the absence of a magnetic field, these spin states are degenerate, meaning that they correspond to the same energy. When an external magnetic field is applied, the energy levels are split, since those spin states that are aligned with the magnetic field will have a different energy than those that are anti-parallel to it.

In the absence of a magnetic field, one would expect such a two-spin system to have roughly half the atoms in the spin-up state and half in the spin-down state, since this maximizes entropy. Upon application of a magnetic field, some of the atoms will tend to align so as to minimize the energy of the system, thus slightly more atoms should be in the lower-energy state (for the purposes of this example we'll assume the spin-down state is the lower-energy state). It is possible to add energy to the spin system using radio frequency (RF) techniques. This causes atoms to flip from spin-down to spin-up. Since we started with over half the atoms in the spin-down state, initially this drives the system towards a 50/50 mixture, so the entropy is increasing, corresponding to a positive temperature. However, at some point more than half of the spins are in the spin-up position. In this case adding additional energy, reduces the entropy since it moves the system further from a 50/50 mixture. This reduction in entropy with the addition of energy corresponds to a negative temperature. For additional information see [1].

Temperature in gases

As mentioned previously for a monatomic ideal gas the temperature is related to the translational motion or average speed of the atoms. The Kinetic theory of gases uses Statistical mechanics to relate this motion to the average kinetic energy of atoms and molecules in the system. For this case 11300 degrees Celsius corresponds to an average kinetic energy of one electronvolt; to take room temperature (300 kelvin) as an example, the average energy of air molecules is 300/11300 eV, or 0.0273 electronvolts. This average energy is independent of particle mass, which seems counterintuitive to many people. Although the temperature is related to the *average* kinetic energy of the particles in a gas, each particle has its own energy which may or may not correspond to the average. In a gas the distribution of energy (and thus speeds) of the particles corresponds to the Boltzmann distribution.

An electronvolt is a very small unit of energy, on the order of 1.602e-19 joules.

Temperature Measurement

Many methods have been developed for measuring temperature. Most of these rely on measuring some physical property of a working material that varies with temperature. One of the most common devices for measuring temperature is the glass thermometer. This consists of a glass tube filled with mercury or some other liquid, which acts as the working fluid. Temperature increases cause the fluid to expand, so the temperature can be determined by measuring the volume of the fluid. Such thermometers are usually calibrated, so that one can read the temperature, simply by observing the level of the fluid in the thermometer. Another type of thermometer that is not really used much in practice, but is important from a theoretical standpoint is the **gas thermometer** mentioned previously.

Other important devices for measuring temperature include:

- Thermocouples
- Thermistors
- Resistance Temperature Detector (RTD)
- Pyrometers
- Other thermometers

One must be careful when measuring temperature to ensure that the measuring instrument (thermometer, thermocouple, etc) is really the same temperature as the material that is being measured. Under some conditions heat from the measuring instrument can cause a temperature gradient, so the measured temperature is different from the actual temperature of the system. In such a case the measured temperature will vary not only with the temperature of the system, but also with the heat transfer properties of the system. An extreme case of this effect gives rise to the wind chill factor, where the weather feels colder under windy conditions than calm conditions even though the temperature is the same. What is happening is that the wind increases the rate of heat transfer from the body, resulting in a larger reduction in body temperature for the same ambient temperature.

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Thermodynamic entropy

This articles treats entropy in thermodynamics. In fact, the two types of entropy are closely related, and their relationship reveals deep connections between thermodynamics and information theory.

The **thermodynamic entropy** *S*, often simply called the **entropy** in the context of chemistry and thermodynamics, is a measure of the amount of energy in a physical system which cannot be used to do work. It is also a measure of the disorder present in a system.

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Thermodynamic definition of entropy

The concept of entropy was introduced in 1865 by Rudolf Clausius. He defined the *change in entropy* of a thermodynamic system, during a *reversible process* in which an amount of heat ´*Q* is applied at constant absolute temperature *T*, as

$$\delta S = \frac{\delta Q}{T}$$

Clausius gave the quantity *S* the name "entropy", from the Greek word ÄÁoÀ®, "transformation". Note that this equation involves only a change in entropy, so the entropy itself is only defined up to an additive constant. Later, we will discuss an alternative definition which uniquely defines the entropy.

Entropy change in heat engines

Clausius' identification of *S* as a significant quantity was motivated by the study of reversible and irreversible thermodynamic transformations. In the next few sections, we will examine the steps leading to this identification, and its consequences for thermodynamics.

A thermodynamic transformation is a change in a system's thermodynamic properties, such as its temperature and volume. A transformation is said to be reversible if, at each successive step of the transformation, the system is infinitesimally close to equilibrium; otherwise, the transformation is said to be irreversible. As an example, consider a gas enclosed in a piston chamber, whose volume may be changed by moving the piston. A reversible volume change is one that takes place so slowly that the density of the gas always remains homogeneous. An irreversible volume change is one that takes place so quickly that pressure waves are created within the gas, which is a state of disequilibrium. Reversible processes are sometimes referred to as quasi-static processes.

A heat engine is a thermodynamic system that can undergo a sequence of transformations which ultimately return it to its original state. This sequence is called a *cycle*. During some transformations, the engine may exchange heat with large systems known as heat reservoirs, which have a fixed temperature and can absorb or provide an arbitrary amount of heat. The net result of a cycle is (i) work done by the system (which may be negative, which is the same as positive work done *on* the system), and (ii) heat transferred between the heat reservoirs. By the conservation of energy, the heat lost by the heat reservoirs is exactly equal to the work done by the engine plus the heat gained by the heat reservoirs.

If every transformation in the cycle is reversible, the cycle is reversible. This means that it can be run in reverse, i.e. the heat transfers occur in the opposite direction and the amount of work done switches sign. The simplest reversible cycle is a Carnot cycle, which exchanges heat with two heat reservoirs.

In thermodynamics, absolute temperature is *defined* in the following way. Suppose we have two heat reservoirs. If a Carnot cycle absorbs an amount of heat Q from the first reservoir and delivers an amount of heat $Q2$ to the second, then the respective temperatures T and $T2$ are given by

Now consider a cycle of an arbitrary heat engine, during which the system exchanges heats Q_1, Q_2, ..., Q_N with a sequence of N heat reservoirs that have temperatures T_1, ..., T_N. We take each Q to be positive if it represents heat received by the system, and negative if it represents heat emitted by the system. We will show that

$$\sum_{i=1}^{N} \frac{Q_i}{T_i} \le 0$$

where the equality sign holds if the cycle is reversible.

To prove this, we introduce an additional heat reservoir at some arbitrary temperature T_0, as well as N Carnot cycles that have the following property: the j-th such cycle operates between the T_0 reservoir and the T_j reservoir, transferring heat Q_j to the latter. From the above definition of temperature, this means that the heat extracted from the T_0 reservoir by the j-th cycle is

$$Q_{0,j} = T_0 \frac{Q_j}{T_j}$$

We now consider one cycle of our arbitrary heat engine, accompanied by one cycle of each of the N Carnot cycles. At the end of this process, each of the reservoirs T_1, ..., T_N have no net heat loss, since the heat extracted by the heat engine is replaced by one of the Carnot cycles. The net result is (i) an unspecified amount of work done by the heat engine, and (ii) a total amount of heat extracted from the T_0 reservoir, equal to

$$Q_0 = \sum_{j=1}^{N} Q_{0,j} = T_0 \sum_{j=1}^{N} \frac{Q_j}{T_j}$$

If this quantity is positive, this process would function as a perpetual motion machine of the second kind. The second law of thermodynamics states that this is impossible, so

$$\sum_{i=1}^{N} \frac{Q_i}{T_i} \leq 0$$

as claimed. It is easy to show that the equality holds if the engine is reversible, by repeating the above argument for the reverse cycle.

It is important to note that we have used T_j to refer to the temperature of each heat reservoir with which the system comes into contact, not the temperature of the system itself. If the cycle is not reversible, then heat always flows from higher temperatures to lower temperatures, so that

$$\frac{Q_j}{T_j} \leq \frac{Q_j}{T}$$

where T is the temperature of the system while it is in thermal contact with the heat reservoir.

However, if the cycle is reversible, the system is always infinitesimally close to equilibrium, so its temperature must be equal to any reservoir with which it is contact. In that case, we may replace each T_j with T. In the limiting case of a reversible cycle consisting of a *continuous* sequence of transformations,

$$\oint \frac{dQ}{T} \equiv \oint dS = 0 \qquad \text{(reversible cycles)}$$

where the integral is taken over the entire cycle, and T is the temperature of the system at each step.

Entropy as a state function

We can now deduce an important fact about the entropy change during *any* thermodynamic transformation, not just a cycle. First, consider a reversible transformation that brings a system from an equilibrium state A to another equilibrium state B. If we follow this with *any* reversible transformation which returns that system to state A, our above result says that the net entropy change is zero. This implies that the entropy change in the first transformation depends *only on the initial and final states*.

This allows us to define the entropy of any *equilibrium* state of a system. Choose a reference state R and call its entropy S_R. The entropy of any equilibrium state X is

$$S_X = S_R + \int_R^X \frac{dQ}{T}$$

Since the integral is independent of the particular transformation taken, this equation is well-defined.

We now consider irreversible transformations. It is straightforward to show that the entropy change during any transformation between two *equilibrium* states is

$$\Delta S \geq \int \frac{dQ}{T}$$

where the equality holds if the transformation is reversible.

Notice that if $dQ = 0$, then ”S e 0. The second law of thermodynamics is sometimes stated as this result: *the total entropy of a thermally isolated system can never decrease*.

Suppose a system is thermally isolated but remains in *mechanical* contact with the environment. If it is not in mechanical equilibrium with the environment, it will do work on the environment, or vice versa. For example, consider a gas enclosed in a piston chamber whose walls are perfect thermal insulators. If the pressure of the gas differs from the pressure applied to the piston, it will expand or contract, and work will be done. Our above result indicates that the entropy of the system will increase during this process (it could in principle remain constant, but this is unlikely.) Typically, there exists a maximum amount of entropy the system may possess under the circumstances. This entropy corresponds to a state of *stable equilibrium*, since a transformation to any other equilibrium state would cause the entropy to decrease, which is forbidden. Once the system reaches this maximum-entropy state, no more work may be done.

Statistical definition of entropy: Boltzmann's Principle

In 1877, Boltzmann realised that the entropy of a system may be related to the number of possible "microstates" (microscopic states) consistent with its thermodynamic properties. Consider, for example, an ideal gas in a container. A microstate is specified with the positions and momenta of each constituent atom. Consistency requires us to consider only those microstates for which (i) the positions of all the particles are located within the volume of the container, (ii) the kinetic energies of the atoms sum up to the total energy of the gas, and so forth. Boltzmann then postulated that

$$S = k(\ln \copyright)$$

where k is known as Boltzmann's constant and © is the number of microstates that are consistent with the given macroscopic state. This postulate, which is known as Boltzmann's principle, may be regarded as the foundation of statistical mechanics, which describes thermodynamic systems using the statistical behaviour of its constituents. It relates a microscopic property of the system (©) to one of its thermodynamic properties (S).

Under Boltzmann's definition, the entropy is clearly a function of state. Furthermore, since © is just a natural number (1,2,3,...), the entropy must be *positive* (this is simply a property of the logarithm.)

Entropy as a measure of disorder

We can view © as a measure of the disorder in a system. This is reasonable because what we think of as "ordered" systems tend to have very few configurational possibilities, and "disordered" systems have very many. Consider, for example, a set of 10 coins, each of which is either heads up or tails up. The most "ordered" macroscopic states are 10 heads or 10 tails; in either case, there is exactly one configuration that can produce the result. In contrast, the most "disordered" state consists of 5 heads and 5 tails, and there are ${}^{10}C_5 = 252$ ways to produce this result.

Under the statistical definition of entropy, the second law of thermodynamics states that the disorder in an isolated system tends to increase. This can be understood using our coin example. Suppose that we start off with 10 heads, and re-flip one coin at random every minute. If we examine the system after a long time has passed, it is *possible* that we will still

see 10 heads, or even 10 tails, but that is not very likely; it is far more probable that we will see approximately as many heads as tails.

Since its discovery, the idea that disorder tends to increase has been the focus of a great deal of thought, some of it confused. A chief point of confusion is the fact that the result ”*S* e 0 applies only to *isolated* systems; notably, the Earth is not an isolated system because it is constantly receiving energy in the form of sunlight. Nevertheless, it has been pointed out that the universe may be considered an isolated system, so that its total disorder should be constantly increasing. It has been speculated that the universe is fated to a heat death in which all the energy ends up as a homogeneous distribution of thermal energy, so that no more work can be extracted from any source.

Counting of microstates

In classical statistical mechanics, the number of microstates is actually infinite, since the properties of classical systems are continuous. For example, a microstate of a classical ideal gas is specified by the positions and momenta of all the atoms, which range continuously over the real numbers. Therefore, a method of "classifying" the microstates must be invented if we are to define ©. In the case of the ideal gas, we count two states of an atom as the "same" state if their positions and momenta are within ´*x* and ´*p* of each other. Since the values of ´*x* and ´*p* can be chosen quite arbitrarily, the entropy is not uniquely defined; it is in fact defined only up to an additive constant, as before. This grouping of microstates is called coarse graining, and has its counterpart in the choice of basis states in quantum mechanics.

This ambiguity is partly resolved with quantum mechanics. The quantum state of a system can be expressed as a superposition of *basis states*, which are typically chosen to be eigenstates of the unperturbed Hamiltonian. In quantum statistical mechanics, © refers to the number of basis states consistent with the thermodynamic properties. Since the set of basis states is generally countable, we can define &Omega.

However the choice of the set of basic states is still somehow arbitrary. It coresponds to the choice of coarse graining of microstates, to the distinct macrostates in classical physics.

This leads to Nernst's theorem, sometimes referred to as the third law of thermodynamics, which states that the entropy of a system at zero absolute temperature is a well-defined constant. This is due to the fact that a system at zero temperature exists in its ground state, so that its entropy is determined by the degeneracy of the ground state. Many systems, such as crystal lattices, have a unique ground state, and therefore have zero entropy at at absolute zero (since ln(1) = 0).

Measuring Entropy

In real experiments, it is quite difficult to measure the entropy of a system. The techniques for doing so are based on the thermodynamic definition of the entropy, and require extremely careful calorimetry.

For simplicity, we will examine a mechanical system, whose thermodynamic state may be specified by its volume *V* and pressure *P*. In order to measure the entropy of a specific state, we must first measure the heat capacity at constant volume and at constant pressure

(denoted C_V and C_P respectively), for a successive set of states intermediate between a reference state and the desired state. The heat capacities are related to the entropy S and the temperature T by

$$C_X = T\left(\frac{\partial S}{\partial T}\right)_X$$

where the X subscript refers to either constant volume or constant pressure. This may be integrated numerically to obtain a change in entropy:

$$\Delta S = \int \frac{C_X}{T}dT$$

We can thus obtain the entropy of any state (P,V) with respect to a reference state (P_0,V_0). The exact formula depends on our choice of intermediate states. For example, if the reference state has the same pressure as the final state,

$$S(P,V) = S(P,V_0) + \int_{T(P,V_0)}^{T(P,V)} \frac{C_P(P,V(T,P))}{T}dT$$

In addition, if the path between the reference and final states lies across any first order phase transition, the latent heat associated with the transition must be taken into account.

The entropy of the reference state must be determined independently. Ideally, one chooses a reference state at an extremely high temperature, at which the system exists as a gas. The entropy in such a state would be that of a classical ideal gas plus contributions from molecular rotations and vibrations, which may be determined spectroscopically. Choosing a *low* temperature reference state is sometimes problematic since the entropy at low temperatures may behave in unexpected ways. For instance, a calculation of the entropy of ice by the latter method, assuming no entropy at zero temperature, falls short of the value obtained with a high-temperature reference state by 3.41 J/K/mol. This is due to the fact that the molecular crystal lattice of ice exhibits geometrical frustration, and thus possesses a non-vanishing "zero-point" entropy at arbitrarily low temperatures.

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Physical information

Physical information refers generally to the information that is contained in a physical system. First, what is information?

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Information

Information itself may be loosely defined as "that which distinguishes one thing from another." The information that is contained in a thing can thus be said to be the *identity* of the particular thing, itself, that is, all of its properties, all that makes it distinct from other (real or potential) things.

Classical vs. Quantum Information

For physical systems, we must distinguish between classical information and quantum information. Quantum information specifies the complete quantum state vector (equivalently, wavefunction) of a system, whereas classical information, roughly speaking, only picks out a quantum state if one is already given a prespecified set of distinguishable (orthogonal) quantum states to choose from; such a set forms a basis for the vector space of all possible (pure) quantum states. Quantum information can thus be considered to consist of (1) a choice of basis such that the actual quantum state is equal to one of the basis vectors, plus (2) the classical information specifying which of these basis vectors is the actual one.

Note that the amount of classical information in a quantum system gives the maximum amount of information that can actually be measured and extracted from that quantum system for use by external classical (decoherent) systems, since only basis states are operationally distinguishable from each other. The impossibility of differentiating between non-orthogonal states is a fundamental principle of quantum mechanics, equivalent to Heisenberg's uncertainty principle. Because of its more general utility, the remainder of this article will deal primarily with classical information, although quantum information theory does also have some potential applications (quantum computing, quantum cryptography, quantum teleportation) that are currently being actively explored by both theoreticians and experimentalists [1].

Classical Information

An amount of (classical) information may be quantified as follows [2]. For a system S, defined abstractly in such a way that it has N distinguishable states (orthogonal quantum states) that are consistent with its description, the amount of information $I(S)$ contained in the system's state can be said to be $\log(N)$. The logarithm is selected for this definition since it has the advantage that this measure of information content is additive when concatenating independent, unrelated subsystems; e.g., if subsystem A has $I(A)=N$ distinguishable states ($\log(N)$ information content) and an independent subsystem B has $I(B)=M$ distinguishable states ($\log(M)$ information content), then the concatenated system has NM distinguishable states and an information content $I(AB) = \log(NM) = \log(N) + \log(M) = I(A) + I(B)$. We expect information to be additive from our everyday associations with the meaning of the word, e.g., that two pages of a book can contain twice as much information as one page.

The base of the logarithm used in this definition is arbitrary, since it affects the result by only a multiplicative constant, which determines the unit of information that is implied. If the log is taken base 2, the unit of information is the binary digit or bit (so named by John Tukey); if we use a natural logarithm instead, we might call the resulting unit the "nat." In magnitude, a nat is apparently identical to Boltzmann's constant k or the ideal gas constant R, although these particular quantities are usually reserved to measure physical information that happens to be entropy, and that are expressed in physical units such as Joules per Kelvin, or kilocalories per mole per Kelvin.

Physical Information and Entropy

An easy way to understand physical entropy itself is as follows: Entropy is simply that part of the (classical) physical information contained in a system whose identity (as opposed to amount) is unknown. This informal characterization fits von Neumann's formal definition of the entropy of a mixed quantum state, as well as Shannon's definition of the entropy of a probability distribution over classical states [2].

Even when the exact state of a system is known, we can say that the information in the system is still effectively entropy if that information is effectively incompressible, that is, if there are no known or feasibly determinable correlations or redundancies between different pieces of information within the system. Note that this definition can be viewed as equivalent to the previous one (unknown information) if we take a meta-perspective and say that for observer A to know the state of system B means simply that there is a definite correlation between the state of observer A and the state of system B; this correlation could be used by a meta-observer to compress his description of the joint system AB [3].

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Transition

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Phase transition

In physics, a **phase transition** is the transformation of a thermodynamic system from one phase to another. The distinguishing characteristic of a phase transition is an abrupt sudden change in one or more physical properties, in particular the heat capacity, with a small change in a thermodynamic variable such as the temperature. Examples of phase transitions are:

- The transitions between the solid, liquid, and gaseous phases (boiling, melting, sublimation, etc.)
- The transition between the ferromagnetic and paramagnetic phases of magnetic materials at the Curie point.
- The emergence of superconductivity in certain metals when cooled below a critical temperature.
- Quantum condensation of bosonic fluids, such as Bose-Einstein condensation and the superfluid transition in liquid helium.
- The breaking of symmetries in the laws of physics during the early history of the universe as its temperature cooled.

As discussed in the article on phases, phase transitions come about when the free energy of a system is non-analytic for some choice of thermodynamic variables. This non-analyticity generally stems from the interactions of an extremely large number of particles in a system, and does not appear in systems that are too small.

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Classification of phase transitions

Ehrenfest classification

The first attempt at classifying phase transitions was the **Ehrenfest classification scheme**, which grouped phase transitions based on the degree of non-analyticity involved. Though useful, Ehrenfest's classification is flawed, as we will discuss in the next section.

Under this scheme, phase transitions were labelled by the lowest derivative of the free energy that is discontinuous at the transition. **First-order phase transitions** exhibit a discontinuity in the first derivative of the free energy with a thermodynamic variable. The various solid/liquid/gas transitions are classified as first-order transitions, as the pressure, which is the first derivative of the free energy with volume, changes discontinuously across the transitions. **Second-order phase transitions** have a discontinuity in a second derivative of the free energy. These include the ferromagnetic phase transition in materials such as iron, where the magnetization, which is the first derivative of the free energy with the appplied magnetic field strength, increases continuously from zero as the temperature is lowered below the Curie temperature. The magnetic susceptibility, the second derivative of the free energy with the field, changes discontinuously. Under the Ehrenfest classication scheme, there could in principle be third, fourth, and higher-order phase transitions.

Modern classification of phase transitions

The Ehrenfest scheme is an inaccurate method of classifying phase transitions, for it is based on the **mean field theory** of phases (to be described in a later section.) Mean field theory is inaccurate in the vicinity of phase transitions, as it neglects the role of thermodynamic fluctuations. For instance, it predicts a finite discontinuity in the heat capacity at the ferromagnetic transition, which is implied by Ehrenfest's definition of "second-order" transitions. In real ferromagnets, the heat capacity diverges to infinity at the transition.

In the modern classification scheme, phase transitions are divided into two broad categories, named similarly to the Ehrenfest classes:

The **first-order phase transitions** are those that involve a latent heat. During such a transition, a system either absorbs or releases a fixed (and typically large) amount of energy. Because energy cannot be instantaneously transferred between the system and its environment, first-order transitions are associated with "mixed-phase regimes" in which some parts of the system have completed the transition and others have not. This phenomenon is familiar to anyone who has boiled a pot of water: the water does not instantly turn into gas, but forms a turbulent mixture of water and water vapor bubbles. Mixed-phase systems are difficult to study, because their dynamics are violent and hard to control. However, many important phase transitions fall in this category, including the solid/liquid/gas transitions.

The second class of phase transitions are the **continuous phase transitions**, also called **second-order phase transitions**. These have no associated latent heat. Examples of second-order phase transitions are the ferromagnetic transition, the superfluid transition, and Bose-Einstein condensation.

Several transitions are known as the **infinite-order phase transitions**. They are continuous but break no symmetries (see **Symmetry** below). The most famous example is the Berezinsky-Kosterlitz-Thouless transition in the two-dimensional XY model. Many quantum phase transitions in two-dimensional electron gases belong to this class.

Properties of phase transitions

Critical points

In systems containing liquid and gaseous phases, there exist a special combination of pressure and temperature, known as the **critical point**, at which the transition between liquid and gas becomes a second-order transition. Near the critical point, the fluid is sufficiently hot and compressed that the distinction between the liquid and gaseous phases is almost non-existent.

This is associated with the phenomenon of critical opalescence, a milky appearance of the liquid, due to density fluctuations at all possible wavelengths (including those of visible light).

Symmetry

Phase transitions often (but not always) take place between phases with different symmetry. Consider, for example, the transition between a fluid (i.e. liquid or gas) and a crystalline solid. A fluid, which is composed of atoms arranged in a disordered but homogenous manner, possesses continuous translational symmetry: each point inside the fluid has the same properties as any other point. A crystalline solid, on the other hand, is made up of atoms arranged in a regular lattice. Each point in the solid is *not* similar to other points, unless those points are displaced by an amount equal to some lattice spacing.

Generally, we may speak of one phase in a phase transition as being more symmetrical than the other. The transition from the more symmetrical phase to the less symmetrical one is a **symmetry-breaking** process. In the fluid-solid transition, for example, we say that continuous translation symmetry is broken.

The ferromagnetic transition is another example of a symmetry-breaking transition, in this case the symmetry under reversal of the direction of electric currents and magnetic field lines. This symmetry is referred to as "up-down symmetry" or "time-reversal symmetry". It is broken in the ferromagnetic phase due to the formation of magnetic domains containing aligned magnetic moments. Inside each domain, there is a magnetic field pointing in a fixed direction chosen spontaneously during the phase transition. The name "time-reversal symmetry" comes from the fact that electric currents reverse direction when the time coordinate is reversed.

The presence of symmetry-breaking (or nonbreaking) is important to the behavior of phase transitions. It was pointed out by Landau that, given any state of a system, one may unequivocally say whether or not it possesses a given symmetry. Therefore, it cannot be possible to analytically deform a state in one phase into a phase possessing a different symmetry. This means, for example, that it is impossible for the solid-liquid phase boundary to end in a critical point like the liquid-gas boundary. However, symmetry-breaking transitions can still be either first or second order.

Typically, the more symmetrical phase is on the high-temperature side of a phase transition, and the less symmetrical phase on the low-temperature side. This is certainly the case for the solid-fluid and ferromagnetic transitions. This happens because the Hamiltonian of a system usually exhibits all the possible symmetries of the system, whereas the low-energy states lack some of these symmetries (this phenomenon is known as spontaneous symmetry breaking.) At low temperatures, the system tends to be confined to the low-energy states. At higher temperatures, thermal fluctuations allow the system to access states in a broader range of energy, and thus more of the symmetries of the Hamiltonian.

When symmetry is broken, one needs to introduce one or more extra variables to describe the state of the system. For example, in the ferromagnetic phase one must provide the net magnetization, whose direction was spontaneously chosen when the system cooled below the Curie point. Such variables are instances of **order parameters**, which will be described later. However, note that order parameters can also be defined for symmetry-nonbreaking transitions.

Symmetry-breaking phase transitions play an important role in cosmology. It has been speculated that, in the hot early universe, the vacuum (i.e. the various quantum fields that fill space) possessed a large number of symmetries. As the universe expanded and cooled, the vacuum underwent a series of symmetry-breaking phase transitions. For example, the electroweak transition broke the SU(2)×U(1) symmetry of the electroweak field into the U(1) symmetry of the present-day electromagnetic field. This transition is important to understanding the asymmetry between the amount of matter and antimatter in the present-day universe (see electroweak baryogenesis.)

Critical exponents and universality classes

Continuous phase transitions are easier to study than first-order transitions due to the absence of latent heat, and they have been discovered to have many interesting properties. The phenomena associated with continuous phase transitions are called **critical phenomena**, due to their association with critical points.

It turns out that continuous phase transitions can be characterized by parameters known as critical exponents. For instance, let us examine the behavior of the heat capacity near such a transition. We vary the temperature *T* of the system while keeping all the other thermodynamic variables fixed, and find that the transition occurs at some critical temperature T_c. When *T* is near T_c, the heat capacity *C* typically has a **power law** behaviour:

$$C \sim |T_c - T|^{-\alpha}$$

The constant ± is the critical exponent associated with the heat capacity. It is not difficult to see that it must be less than 1 in order for the transition to have no latent heat. Its actual value depends on the type of phase transition we are considering. For -1 < ± < 0, the heat capacity has a "kink" at the transition temperature. This is the behavior of liquid helium at the "lambda transition" from a normal state to the superfluid state, for which experiments have found ± = -0.013±0.003. For 0 < ± < 1, the heat capacity diverges at the transition temperature (though, since ± < 1, the divergence is not strong enough to produce a latent heat.) An example of such behavior is the 3-dimensional ferromagnetic phase transition. In the three-dimensional Ising model for uniaxial magnets, detailed theoretical studies have yielded the exponent ± 0.110.

Some model systems do not obey this power law behavior. For example, mean field theory predicts a finite discontinuity of the heat capacity at the transition temperature, and the two-dimensional Ising model has a logarithmic divergence. However, these systems are an exception to the rule. Real phase transitions exhibit power law behavior.

Several other critical exponents - ², ³, ´, ½, and · - are defined, examining the power law behavior of a measurable physical quantity near the phase transition.

It is a remarkable fact that phase transitions arising in different systems often possess the same set of critical exponents. This phenomenon is known as **universality**. For example, the critical exponents at the liquid-gas critical point have been found to be independent of the chemical composition of the fluid. More amazingly, they are an exact match for the critical exponents of the ferromagnetic phase transition in uniaxial magnets. Such systems are said to be in the same **universality class**. Universality is a prediction of the renormalization group theory of phase transitions, which states that the thermodynamic properties of a system near a phase transition depend only on a small number of features, such as dimensionality and symmetry, and is insensitive to the underlying microscopic properties of the system.

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Critical phenomena

Critical phenomena occur at the critical point. Often the words "critical phenomena" are also used for any condensed matter systems with an infinite correlation length. Most important critical phenomena include universality, scaling, spontaneous symmetry breaking, and topological orders.

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Spontaneous symmetry breaking

Suppose we have some laws describing how possible states ought to behave and they are symmetric under a certain group. But suppose, however, the lowest energy solution, i.e. the stable solution is not symmetric under that group. This obviously means the lowest energy state is degenerate and performing a symmetry transformation on any such state would just lead to another such state. However, from the point of view of an observer in a state close to one of these states, it looks as if the symmetry of the dynamical laws are broken.

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Superconductivity

Superconductivity is an electromagnetic phenomenon occurring in certain materials at low temperatures, characterized by the complete absence of electrical resistance and the damping of the interior magnetic field (the Meissner effect.)

Superconductivity occurs in a wide variety of materials, including simple elements like tin and aluminum, various metallic alloys, some heavily-doped semiconductors, and certain ceramic compounds containing planes of copper and oxygen atoms. The latter class of compounds, known as the cuprates, are high-temperature superconducters. Superconductivity does not occur in noble metals like gold and silver, nor in ferromagnetic metals such as iron (although iron can be turned into a superconductor by subjecting it to very high pressures).

In conventional superconductors, superconductivity is caused by a force of attraction between certain conduction electrons arising from the exchange of phonons, which causes the fluid of conduction electrons to exhibit a superfluid phase composed of correlated *pairs* of electrons. There also exists a class of materials, known as unconventional

superconductors, that exhibit superconductivity but whose physical properties contradict the theory of conventional superconductors. In particular, the so-called high-temperature superconductors superconduct at temperatures much higher than should be possible according to the conventional theory (though still far below room temperature.) There is currently no complete theory of high-temperature superconductivity.

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Elementary properties of superconductors

Most of the physical properties of superconductors vary from material to material, such as the heat capacity and the critical temperature at which superconductivity is destroyed. On the other hand, there is a class of properties that are independent of the underlying material. For instance, all superconductors have *exactly* zero resistivity to low applied currents when there is no magnetic field present. The existence of these "universal" properties imply that superconductivity is a thermodynamic phase, and thus possess certain distinguishing properties which are largely independent of microscopic details.

Zero electrical resistance

Suppose we were to attempt to measure the electrical resistance of a piece of superconductor. The simplest method is to place the sample in an electrical circuit, in series with a voltage source V (such as a battery), and measure the resulting current. If we carefully account for the resistance R of the remaining circuit elements (such as the leads connecting the sample to the rest of the circuit), we would find that the current is simply V/R. According to Ohm's law, this means that the resistance of the superconducting sample is zero.

In a normal conductor, an electrical current may be visualized as a fluid of electrons moving across a heavy ionic lattice. The electrons are constantly colliding with the ions in

the lattice, and during each collision some of the energy carried by the current is absorbed by the lattice and converted into heat (which is essentially the vibrational kinetic energy of the lattice ions.) As a result, the energy carried by the current is constantly being dissipated. This is the phenomenon of electrical resistance.

The situation is different in a superconductor. In a conventional superconductor, the electronic fluid cannot be resolved into individual electrons, instead consisting of bound *pairs* of electrons known as **Cooper pairs**. This pairing is caused by an attractive force between electrons from the exchange of phonons. Due to quantum mechanics, the energy spectrum of this Cooper pair fluid possesses an *energy gap*, meaning there is a minimum amount of energy *”E* that must be supplied in order to excite the fluid. Therefore, if *”E* is larger than the thermal energy of the lattice (given by kT, where k is Boltzmann's constant and T is the temperature), the fluid will not be scattered by the lattice. The Cooper pair fluid is thus a superfluid, meaning it can flow without energy dissipation. Experiments have in fact demonstrated that currents in superconducting rings persist for years without any measurable degradation.

(Note: actually, in a class of superconductors known as type II superconductors, a small amount of resistivity appears when a strong magnetic field and electrical current are applied. This is due to the motion of vortices in the electronic superfluid, which dissipates some of the energy carried by the current. If the current is sufficiently small, the vortices are stationary, and the resistivity vanishes.)

Superconducting phase transition

In superconducting materials, the characteristics of superconductivity appear when the temperature T is lowered below a **critical temperature** T_c. The value of this critical temperature varies from material to material. Conventional superconductors usually have critical temperatures ranging from less than 1K to around 20K. Solid mercury, for example, has a critical temperature of 4.2K. As of 2001, the highest critical temperature found for a conventional superconductor is 39K for magnesium boride (MgB_2), although this material displays enough exotic properties that there is doubt about classifying it as a "conventional" superconductor. Cuprate superconductors can have much higher critical temperatures: $YBa_2Cu_3O_7$, one of the first cuprate superconductors to be discovered, has a critical temperature of 92K, and mercury-based cuprates have been found with critical temperatures in excess of 130K. The explanation for these high critical temperatures remains unknown.

The onset of superconductivity is accompanied by abrupt changes in various physical properties, which is the hallmark of a phase transition. For example, the electronic heat capacity is proportional to the temperature in the normal (non-superconducting) regime. At the superconducting transition, it suffers a discontinuous jump and thereafter ceases to be linear. At low temperatures, it varies instead as $e^{-\pm/T}$ for some constant ±. (This exponential behavior is one of the pieces of evidence for the existence of the energy gap.)

The order of the superconducting phase transition is still a matter of debate. It had long been thought that the transition is second-order, meaning there is no latent heat. However,

recent calculations have suggested that it may actually be weakly first-order due to the effect of long-range fluctuations in the electromagnetic field.

Meissner effect

When a superconductor is placed in a weak external magnetic field **H**, the field penetrates for only a short distance », called the **penetration depth**, after which it decays rapidly to zero. This is called the **Meissner effect**. For most superconductors, the penetration depth is on the order of a thousand angstroms (10^{-7}m.)

The Meissner effect is sometimes confused with the "perfect diamagnetism" one would expect in a perfect electrical conductor: according to Lenz's law, when a *changing* magnetic field is applied to a conductor, it will induce an electrical current in the conductor that creates an opposing magnetic field. In a perfect conductor, an arbitrarily large current can be induced, and the resulting magnetic field exactly cancels the applied field.

The Meissner effect is distinct from perfect diamagnetism because a superconductor expels *all* magnetic fields, not just those that are changing. Suppose we have a material in its normal state, containing a constant internal magnetic field. When the material is cooled below the critical temperature, we would observe the abrupt expulsion of the internal magnetic field, which we would not expect based on Lenz's law.

The Meissner effect was explained by London and London, who showed that the electromagnetic free energy in a superconductor is minimized provided

$$\nabla^2 \mathbf{H} = \lambda^{-2} \mathbf{H}$$

where **H** is the magnetic field and » is the penetration depth. This equation, which is known as the London equation, predicts that the magnetic field in a superconductor decays exponentially from whatever value it possesses at the surface.

The Meissner effect breaks down when the applied magnetic field is too large. Superconductors can be divided into two classes according to how this breakdown occurs. In **Type I** superconductors, superconductivity is abruptly destroyed when the strength of the applied field rises above a critical value H_c. Depending on the geometry of the sample, one may obtain an **intermediate state** consisting of regions of normal material carrying a magnetic field mixed with regions of superconducting material containing no field. In **Type II** superconductors, raising the applied field past a critical value H_{c1} leads to a **mixed state** in which an increasing amount of magnetic flux penetrates the material, but there remains no resistance to the flow of electrical current as long as the current is not too large. At a second critical field strength H_{c2}, superconductivity is destroyed. The mixed state is actually caused by vortices in the electronic superfluid, sometimes called "fluxons" because the flux carried by these vortices is quantized. Most pure elemental superconductors (except niobium) are Type I, while almost all impure and compound superconductors are Type II.

Theories of superconductivity

Since the discovery of superconductivity, great efforts have been devoted to finding out how and why it works. During the 1950s, theoretical condensed matter physicists arrived at a solid understanding of "conventional" superconductivity, through a pair of remarkable and important theories: the phenomenological Ginzburg-Landau theory (1950) and the microscopic BCS theory (1957).

History of superconductivity

Superconductivity was discovered in 1911 by Onnes, who was studying the resistivity of solid mercury at cryogenic temperatures using the recently-discovered liquid helium as a refrigerant. At the temperature of 4.2K, he observed that the resistivity abruptly disappeared. For this discovery, he was awarded the Nobel Prize in Physics in 1913.

In subsequent decades, superconductivity was found in several other materials. In 1913, lead was found to superconduct at 7K, and in 1941 niobium nitride was found to superconduct at 16K.

The next important step in understanding superconductivity occurred in 1933, when Meissner and Oschenfeld discovered that superconductors expelled applied magnetic fields, a phenomenon which has come to be known as the Meissner effect. In 1935, F. and H. London showed that Meissner effect was a consequence of the minimization of the electromagnetic free energy carried by superconducting current.

In 1950, the phenomenological Ginzburg-Landau theory of superconductivity was devised by Landau and Ginzburg. This theory, which combined Landau's theory of second-order phase transitions with a Schrödinger-like wave equation, had great success in explaining the macroscopic properties of superconducters. In particular, Abrikosov showed that Ginzburg-Landau theory predicts the division of superconductors into the two categories now referred to as Type I and Type II. Abrikosov and Ginzburg were awarded the Nobel Prize for these works in 2003.

Also in 1950, Maxwell and Reynolds *et. al.* found that the critical temperature of a superconductor depends on the isotopic mass of the constituent element. This important discovery pointed to the electron-phonon interaction as the microscopic mechanism responsible for superconductivity.

The complete microscopic theory of superconductivity was finally proposed in 1957 by Bardeen, Cooper, and Schrieffer. This BCS theory explained the superconducting current as a superfluid of "Cooper pairs", pairs of electrons interacting through the exchange of phonons. For this work, the authors were awarded the Nobel Prize in 1972.

The BCS theory was set on a firmer footing in 1958, when Bogoliubov showed that the BCS wavefunction, which had originally been derived from a variational argument, could be obtained using a canonical transformation of the electronic Hamiltonian. In 1959, Gor'kov showed that the BCS theory reduced to the Ginzburg-Landau theory close to the critical temperature.

In 1962, the first commercial superconducting wire, a niobium-titanium alloy, was developed by researchers at Westinghouse. In the same year, Josephson made the important

theoretical prediction that a supercurrent can flow between two pieces of superconductor separated by a thin layer of insulator. This phenomenon, now called the Josephson effect, is exploited by superconducting devices such as SQUIDs. It is used in the most accurate available measurements of the magnetic flux quantum h/e, and thus (coupled with the quantum Hall resistivity) for Planck's constant h. Josephson was awarded the Nobel Prize for this work in 1973.

In 1986, Bednorz and Mueller discovered superconductivity in a lanthanum-based cuprate perovskite material, which had a transition temperature of 35K (Nobel Prize in Physics, 1987). It was shortly found that replacing the lanthanum with yttrium raised the critical temperature to 92K, which was important because liquid nitrogen could then be used as a refrigerant (at atmospheric pressure, the boiling point of nitrogen is 77K.) Many other cuprate superconductors have since been discovered, and the theory of superconductivity in these materials is one of the major outstanding challenges of theoretical condensed matter physics.

Technological applications of superconductivity

Some technological innovations benefiting from the discovery of superconductivity include sensitive magnetometers based on SQUIDs, digital circuits (e.g. based on the RSFQ logic), Magnetic Resonance Imaging, beam-steering magnets in particle accelerators, electric power transmission cables, and microwave filters (e.g., for mobile phone base stations). Promising future industrial and commercial applications include transformers, power storage, electric motors, and magnetic levitation devices. Most applications employ the well-understood conventional superconductors, but it is expected that high-temperature superconductors will soon become more cost-effective in many cases.

See also: Timeline of low temperature technology.

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Superfluid

Superfluidity is a state of matter characterised by the complete absence of viscosity. Thus superfluids, placed in a closed loop, can flow endlessly without friction. Superfludity was discovered by Pyotr Leonidovich Kapitsa, John F. Allen, and Don Misener in 1937.

The superfluid transition is displayed by quantum liquids below a characteristic transition temperature. The most abundant isotope of Helium, ^{4}He, becomes superfluid at temperatures below 2.17K (-270.98°C). The less abundant isotope, ^{3}He, becomes superfluid at a much lower temperature: 2.6mK (only a few thousandths of a degree above the absolute zero, that is -273.15°C).

Although the phenomenology of superfluidity in these two systems is very similar, the nature of the two superfluid transitions is very different. ^{4}He atoms are bosons, and their superfluidity can be understood in terms of the Bose statistics that they obey. Specifically, the superfluidity of ^{4}He can be regarded as the generalisation of Bose-Einstein condensation (which takes place only in a non-interacting gas) to interacting systems. On the other hand, ^{3}He atoms are fermions, and the superfluid transition in this system is described by a generalisation of the BCS theory of superconductivity. In it, Cooper pairing takes place between atoms rather than electrons, and the attractive interaction between them is mediated by spin fluctuations rather than phonons. A unified description of superconductivity and superfluidity is possible in terms of Gauge symmetry breaking.

One important application of superfluidity is in dilution refrigerators.

The study of superfluidity is quantum hydrodynamics.

Recently in the field of chemistry, superfluid helium-4 has been successfully used in spectroscopic techniques, as a quantum solvent. Referred to as Superfluid Helium Droplet Spectroscopy (SHeDS), it's of great interest in studies of gas molecules, as a single molecule solvated in a superfluid medium allows a molecule to have effective rotational freedom - allowing it to behave exactly as it would in the gas phase.

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Quantum phase transitions

Quantum phase transitions are changes in matter that occur because of quantum behaviour. As opposed to classical behaviour (see classical physics and phase changes). Normally only relevant at temperatures close to absolute zero. For certain types of material Quantum Phase transitions are important, for example the Bose-Einstein Condensate.

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Law of physics

A **Law of physics** is a mathematical relationship between measurable quantities that describe the physical state and properties of bodies. This is a fundamental concept in physics.

Collectively, the **laws of physics** are those physical theories which have been widely published and tested, and are considered by the scientific community in general to be valid. They also tend to be very general, basic theories: instead of having a large list of laws governing many different phenomena in different circumstances, special cases are arrived at through a generalization of basic ideas. Well-known laws of physics include Einstein's Theory of General Relativity, Newton's Laws of Motion, Maxwell's Equations for Electricity and Magnetism, and the theory of Quantum Mechanics.

Interestingly, these so-called "laws" can essentially be viewed as a series of approximations: well-established physical laws are found to be invalid in some special cases, and the new theory created to explain these discrepencies can be said to have generalized the original, rather than superseded it. One well-known example is that of Newton's law of gravity: while it described the world accurately in most normal circumstances, such as the movement of the planets around the sun, it was found to be inaccurate when applied to very large masses or very high velocities. Einstein developed the theory of general relativity, which accurately handled gravitational interactions both those extreme conditions and in the range occupied by Newton's law. However, Newton's formula for gravity is still used in most circumstances, as an easier-to-calculate approximation of gravitational interaction. The same phenomena can be observed when comparing Maxwell's Equations with the theory of quantum electrodynamics, and in other cases.

See *History of Physics*.

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Fundamental force

In physics, four **fundamental forces** are known thus far:

1) Gravity is by far the weakest force, but is the force that has the greatest large-scale impact on the universe. Unlike the other forces, gravity works universally on all matter and energy, and is (so far as we know) universally attractive. Any matter or energy anywhere and at any time in the universe attracts all other matter and energy in the universe, as long as it is inside its light cone. This is explained in detail in General Relativity, which describes gravity in terms of spacetime. One active area of research involves merging the theories of general relativity and quantum mechanics into a more general theory of quantum gravity. It is widely believed that in a theory of quantum gravity, gravity would be mediated by a particle which is known as the graviton.

An interesting theory, negative gravity (also called dark energy), arose while trying to explain the recent discovery that the expansion of the universe is actually *accelerating*.

2) Electromagnetism is the combination of electrostatic and magnetic forces. It is the force between charged particles, such as the force between two electrons, or the force between two current carrying wires. The quantum theory of electromagnetism is known as quantum electrodynamics (QED). In QED, virtual photons transfer this force.

3) The weak nuclear force mediates beta decay. The weak force is transferred by W and Z bosons. Neutrinos interact with other matter only through the weak nuclear force and gravity, and hence can pentrate large amounts of matter without being scattered. Electromagnetism and the weak force can be seen as two aspects of the same underlying force, the electroweak force.

4) The strong nuclear force is the force holding together the protons and neutrons inside the atomic nucleus. The strong force is transferred by gluons and it acts on particles that carry "color charge", i.e. quarks and gluons.

Most particle physicists perceive the existence of different forces each with separate theories to describe them to be inelegant and believe that all of the forces can be described in a general theory of everything. In the late 1960s and early 1970s, a successful theory which forms part of the standard model was proposed to unify electromagnetism and the weak force into a single electroweak force. There is also active work on various forms of grand unified theories which attempt to unite the strong and electroweak forces. Many of these theories predict proton decay which has not been observed.

Much more speculative are theories that attempt to reconcile quantum field theory with General Relativity, in order to find a successful theory for quantum gravity, and then to combine this into a general theory of everything. Unlike grand unified theories, most propsed theories of everything do not yet give experimentally testable predictions.

What physical scientists call the four **fundamental forces** of nature are:

Name - Relative Magnitude - Behavior

Strong nuclear force - 10^{40} - $1/r^7$

Electromagnetic force - 10^{38} - $1/r^2$

Weak nuclear force - 10^{15} - $1/r^{5-7}$

Gravity - 10^{0} - $1/r^{2}$

It is currently believed that all interactions can be explained in terms of these four forces. For instance, friction is a result of the electromagnetic force.

However, an exotic fifth force has been proposed by some physicists from time to time, mostly to explain discrepancies between predicted and measured values of the gravitational constant. As of 2003, all of the experiments which seem to indicate a fifth force have been explainable in terms of experimental errors.

Also of note is that all four of these forces are conservative forces which is to say that the effect of the force on an object moving from one point to another is independent of the path of the object.

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Gravity

Gravitation is the force of attraction that exists between all particles with mass in the universe. It is the force of gravity which is responsible for holding objects onto the surface of planets and, with Newton's law of inertia is responsible for keeping objects in orbit around one another.

"Gravity is the force that pulls you down." -- Merlin in Disney's *The Sword in the Stone*

Merlin was right, of course, but gravity does much more than just hold you in your chair. It was the genius of Isaac Newton to recognize that. Newton recalled in a late memoir that while he was trying to figure out what kept the Moon in the sky, he saw an apple fall to the ground in his orchard, and he realized that the Moon was not suspended in the sky, but continuously falling, like a cannon ball that was shot so fast that it continuously misses the ground as it falls away due to the curvature of the Earth.

If one wishes to be precise, one should distinguish between *gravitation*, the universal force of attraction, and *gravity*, which is the resultant, on the Earth's surface, of the attraction by the earth's masses, and the centrifugal pseudo-force caused by the Earth's rotation. In casual discussion, *gravity* and *gravitation* are often used interchangeably.

By Newton's third law, any two objects exert equal and oppositely directed gravitational pull on each other.

Speed of gravity: Einstein's theory of relativity predicts that the speed of gravity (defined as the speed at which changes in location of a mass are propagated to other masses) should be consistent with the speed of light. In 2002, the Fomalont-Kopeikin experiment produced measurements of the speed of gravity which matched this prediction. However, this experiment has not yet been widely peer-reviewed, and is facing criticism from those who claim that Fomalont-Kopeikin did nothing more than measure the speed of light in a convoluted manner.

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Newton's Law of Universal Gravitation

Newton explains, *"Every object in the Universe attracts every other object with a force directed along the line of centers for the two objects that is proportional to the product of their masses and inversely proportional to the square of the separation between the two objects."*

Newton eventually published his still famous law of universal gravitation in his Principia Mathematica as follows:

$$F = \frac{Gm_1m_2}{r^2}$$

where:

- F = gravitational force between two objects
- m_1 = mass of first object
- m_2 = mass of second object
- r = distance between the objects
- G = universal constant of gravitation

Strictly speaking, this law applies only to point-like objects. If the objects have spatial extent, the true force has to be found by integrating the forces between the various points.

Vector Form

The above form is a simplified version. It is more properly expressed as vector equation. (All quantities in **bold** represent vector quantities in what follows.) The form below is vectorially complete:

$$F_{12} = \frac{Gm_1m_2(\mathbf{r_2} - \mathbf{r_1})}{|\mathbf{r_2} - \mathbf{r_1}|^3}$$

where:

- F_{12} is the force on m_1 by m_2
- m_1 and m_2 are the masses
- $\mathbf{r}_1$ and $\mathbf{r}_2$ are the position vectors of their respective masses
- G is the gravitational constant

For the force on mass two, simply multiply F_{12} by -1.

The primary difference between the two formulations is that the second form uses the difference in position to construct a vector that points from one mass to the other, and then divides that vector by its length to prevent it from changing the magnitude of the force.

Newton's Reservations

It's important to understand that while Newton was able to formulate his law of gravity in his monumental work, he was not comfortable with it because he never, in his words, "assigned the cause of this power." In all other cases, he used the phenomenon of motion to explain the origin of various forces acting on bodies, but in the case of gravity, he was unable to experimentally identify the motion that produces the force of gravity. Moreover, he refused to even offer a hypothesis as to the cause of this force on grounds that to do so was contrary to sound science.

He lamented the fact that 'philosophers have hitherto attempted the search of nature in vain' for the source of the gravitational force, as he was convinced 'by many reasons' that there were 'causes hitherto unknown' that were fundamental to all the 'phenomena of nature.' These fundamental phenomena are still under investigation and, though hypotheses abound, the definitive answer is yet to be found. While it is true that Einstein's hypotheses (see below) are successful in explaining the effects of gravitational forces more precisely than Newton's in certain cases, he too never 'assigned the cause of this power,' in his theories. It is said that in Einstein's equations, 'matter tells space how to curve, and space tells matter how to move,' but this new idea, completely foreign to the world of Newton, does not enable Einstein to assign the 'cause of this power' to curve space anymore than the Law of Universal Gravitation enabled Newton to assign its cause. In his own words:

I wish we could derive the rest of the phenomena of nature by the same kind of reasoning from mechanical principles; for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain.

If science is eventually able to discover the cause of the gravitational force, Newton's wish could eventually be fullfiled as well.

Comparison with electromagnetic force

The gravitational attraction of protons is approximately a factor 10^{36} weaker than the electromagnetic repulsion. This factor is independent of distance, because both forces are inversely proportional to the square of the distance. Therefore on an atomic scale mutual gravity is negligible. However, the main force beween common objects and the earth and between celestial bodies is gravity; this is due to the fact that they (at least one of the two) are electrically neutral to a high degree: even if in both bodies there were a surplus or deficit of only one electron for every 10^{18} protons and neutrons this would already be enough to cancel gravity (or in the case of a surplus in one and a deficit in the other: double the attraction).

The relative weakness of gravity can be demonstrated with a small magnet picking up pieces of iron. The small magnet is able to overwhelm the gravitational force of the entire earth.

Gravity is small unless at least one of the two bodies is large, but the small gravitational force exerted by bodies of ordinary size can fairly easily be detected through experiments such as the Cavendish torsion bar experiment.

Self-gravitating system

A self-gravitating system is a system of masses kept together by mutual gravity. An example is a star.

History

Nobody knows for sure if Newton's recollection about the apple was accurate, but his insight is the same nevertheless. Philosophers had thought since the Greeks that the "natural" movement of stars, planets, the Sun and the Moon was circular, Kepler established that orbits are actually elliptical, but still thought that the movements of the planets was dictated by some "divine force" emanated from the sun, but Newton realized that the same force that causes a thrown rock to fall back to the Earth keeps the planets in orbit of the Sun, and the Moon in orbit of the Earth.

Newton was not alone in making significant contributions to the understanding of gravity. Before Newton, Galileo Galilei corrected a common misconception, started by Aristotle, that objects with different mass fall at different rates. To Aristotle, it simply made sense that objects of different mass would fall at different rates, and that was enough for him. Galileo, however, actually tried dropping objects of different mass at the same time. Aside from differences due to friction from the air, Galileo observed that all masses accelerate the same. Using Newton's equation, $F = ma$, it is plain to us why:

$$F = \frac{Gm_1m_2}{r^2} = m_1a_1$$

The above equation says that mass m_1 will accelerate at acceleration a_1 under the force of gravity, but divide both sides of the equation by m_1 and:

$$a_1 = \frac{Gm_2}{r^2}$$

Nowhere in the above equation does the mass of the falling body appear. When dealing with objects near the surface of a planet, the change in r divided by the initial r is so small that the acceleration due to gravity appears to be perfectly constant. The acceleration due to gravity on Earth is usually called g, and its value is about 9.8 m/s^2 (or 32 ft/s^2). Galileo didn't have Newton's equations, though, so his insight into gravity's proportionality to mass was invaluable, and possibly even affected Newton's formulation on how gravity works.

However, across a large body, variations in r can create a significant tidal force.

Einstein's General Theory of Relativity

Newton's formulation of gravity is quite accurate for most practical purposes. It has a few problems with it though:

1. It assumes that changes in the gravitational force are transmitted instantaneously when positions of gravitating bodies change. However, this contradicts the fact that there exists a maximum velocity at which signals can be transmitted (speed of light in vacuum).
2. Assumption of absolute space and time contradicts Einstein's theory of Special relativity.
3. It predicts that light is deflected by gravity only half as much as observed.
4. It does not explain gravitational waves or black holes.
5. Under newtonian gravity (with instantaneous transmission of gravitational force), if the Universe is Euclidean, static, of uniform, average, positive density and infinite, then the total gravitational force on a point is a divergent series. In other words, newtonian gravity is inconsistent with a Universe which is Euclidean, static, of uniform, average, positive density and infinite.

For the first two of these reasons, Einstein and Hilbert developed a new theory of gravity called General Relativity, published in 1915. This theory predicts that the presence of matter "warps" the local space-time environment, so that apparently "straight" lines through space and time have the properties we think of "curved" lines as having.

Although General Relativity is, as a theory, more accurate than Newton's law of gravity, it also requires a significantly more complicated mathematical formalism. Instead of describing the effect of gravitation as a "force", Einstein introduced the concept of curved space-time in which bodies move along curved trajectories.

Today General Relativity is accepted as the standard description of classical gravitational phenomena. (Alternative theories of gravitation exist but are more complicated than General Relativity.) General Relativity is consistent with all currently available measurements. For weak gravitational fields and bodies moving at slow speeds at small distances, Einstein's General Relativity gives almost exactly the same predictions as Newton's law of gravitation. Crucial experiments that justified the adoption of General Relativity over Newtonian gravity

were the gravitational redshift, the deflection of light rays by the Sun, and the precession of the orbit of Mercury.

More recent experimental confirmations of General Relativity were gravitational waves from orbiting binary stars, the existence of neutron stars and black holes, gravitational lensing, and the convergence of measurements in observational cosmology to an **approximately** flat model of the observable Universe, with a matter density parameter of approximately 30% of the critical density and a cosmological constant of approximately 70% of the critical density.

Quantum Mechanics and Waves

Gravity is the only one of the four fundamental forces of nature that stubbornly refuses to be quantised (the other three: Electromagnetism, the Strong Force, and the Weak Force, can be quantised). Quantisation means that the force is measured in discrete steps that cannot be reduced in size, no matter what; alternatively, that gravitational interaction is trasmitted by particles called gravitons. Scientists have theorized about the graviton for years, but have been frustrated in their attempts to find a consistent quantum theory for it. Many believe that string theory holds a great deal of promise to unify general relativity and quantum mechanics, but this promise has yet to be realized.

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Weak nuclear force

The **weak nuclear force** or **weak interaction** is one of the four fundamental forces of nature. It is most commonly thought to be the cause of beta decay and the associated radioactivity. It is carried by the W bosons (W^+ and W^-) and Z bosons (Z^0).

The weak interaction affects:

- neutrinos
- charged leptons
- quarks

The weak interaction enables all lepton and quark particles and antiparticles to interchange energy, mass and charge - effectively change into each other.

With a field strength some 10^9 times less than the strong nuclear force (10^{-18} m), its influence is limited to action within the atomic nucleus. This short range is explained by the large mass of the weak exchange particles (about 90 GeV).

The electromagnetic force and the weak nuclear force can be described as two different aspects of a single electroweak force.

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Strong interaction

The **strong nuclear force** or **strong interaction** is a fundamental force of nature which affects only quarks, antiquarks, and gluons. This force is responsible for binding quarks together to form hadrons (including protons and neutrons), and the residual effects also bind these neutrons and protons together in the nucleus of the atom. See particle physics for an overview of the theory.

According to quantum chromodynamics, every quark carries *color charge* which comes in three types: "red", "green" and "blue". These are just names and not related to ordinary colors in any way. Antiquarks are either "anti-red", "anti-green" or "anti-blue". Like colors repel, unlike colors attract. The attraction between a color and its anti-color is especially strong. Particles can only exist if their total color is neutral, meaning that they can either be composed of a red, green and blue quark (such a particle is called a baryon; protons and neutrons are examples), or of a quark and an anti-quark having the corresponding anti-color (such a particle is called a meson).

The strong interaction acts between two quarks by exchanging particles called gluons. There are eight types of gluons, each carrying a color charge and an anti-color charge.

As pairs of quarks interact, they constantly change their color, but in such a way that the total color charge is conserved. If say a red quark is attracted to a green quark inside a baryon, a gluon carrying anti-green and red color is emitted from the red quark and absorbed by the green quark; as a result the first quark switches to green and the second to red (total color charge remains green + red). If a blue quark and a anti-blue antiquark interact inside a meson, a gluon carrying for example anti-red and blue could be emitted by the blue quark and absorbed by the anti-blue one; as a result the blue quark turns red and the anti-blue antiquark turns anti-red (total color charge remains 0). Two green quarks repel each other by exchanging a gluon carrying green and anti-green color; the quarks remain green.

Unlike the other fundamental forces, the strong interaction also acts on the strong exchange particles themselves, since gluons carry color charge. This leads to a very limited range of the strong interaction (not much farther than the hadron's radius) even though the gluon does not have mass. It also has the strange effect that the force gets stronger as the distance between the quarks increases. This effect prevents free quarks from being observed. As the distance between two quarks increases, the amount of energy in the force between them increases. If the force becomes strong enough, there is enough energy to create new quarks. This is the reason that one only sees quarks in pairs or triplets and never individually. The textbook allegory is that of a rubber band. When the rubber band is stretched far enough, the band breaks and you have two new rubber bands. Similar with quarks: separate the quark pair far enough, and two new quarks will pop up.

The phenomenon of not being able to separate quarks, is called confinement. It is conjectured as the quarks are moved really close, the quarks no longer interact via the strong interaction, and become `free' - this is called asymptotic freedom. The allegory of the rubber band holds here too. Move the ends of the band close together, and they do not `feel' each other.

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Particle

In particle physics, an **elementary particle** is a particle of which other, larger particles are composed. For example, atoms are made up of smaller particles known as electrons, protons, and neutrons. The proton and neutron, in turn, are composed of more elementary particles known as quarks. One of the outstanding problems of particle physics is to find the most elementary particles — or the so-called **fundamental particles** — which make up all the other particles found in Nature, and are not themselves made up of smaller particles.

Standard Model

The Standard Model of particle physics contains 12 flavours of elementary fermions ("matter particles"), plus their corresponding antiparticles, as well as elementary bosons that mediate the forces and the still undiscovered Higgs boson. However, the Standard Model is widely considered to be a provisional theory rather than a truly fundamental one, since it is fundamentally incompatible with Einstein's general relativity. There are likely to be hypothetical elementary particles not described by the Standard Model, such as the graviton, the particle that would carry the gravitational force or the sparticles, supersymmetric partners of the ordinary particles.

Fundamental fermions

Main article: fermion

The 12 fundamental fermionic flavours are divided into three generations of four particles each. Six of the particles are quarks. The remaining six are leptons, three of which are neutrinos, and the remaining three of which have an electric charge of 1: the electron and its two cousins, the muon and the tau lepton.

Particle Generations

First generation	*Second generation*	*Third generation*
• electron: *e*	• muon: ¼	• tau lepton: Ä
• electron-neutrino: $½_e$	• muon-neutrino: $½_{¼}$	• tau-neutrino: $½_{Ä}$
• up quark: *u*	• charm quark: *c*	• top quark: *t*
• down quark: *d*	• strange quark: *s*	• bottom quark: *b*

Antiparticles

Main article: antimatter

There are also 12 fundamental fermionic antiparticles which correspond to these 12 particles. The positron e^+ corresponds to the electron and has an electric charge of +1 and so on:

Antiparticles

First generation	*Second generation*	*Third generation*

- positron: e^+
- electron-antineutrino: $\bar{\nu}_e$
- up antiquark: $\bar{u}$
- down antiquark: $\bar{d}$
- positive muon: ¼+
- muon-antineutrino: $\bar{\nu}_\mu$
- charm antiquark: $\bar{c}$
- strange antiquark: $\bar{s}$
- positive tau lepton: Ä+
- tau-antineutrino: $\bar{\nu}_\tau$
- top antiquark: $\bar{t}$
- bottom antiquark: $\bar{b}$

Quarks

Main article: quark

Quarks and antiquarks have never been detected to be isolated, a fact explained by confinement. Every quark carries one of three color charges of the strong interaction; antiquarks similarly carry anticolor. Color charged particles interact via gluon exchange in the same way that charged particles interact via photon exchange. However, gluons are themselves color charged, resulting in an amplification of the strong force as color charged particles are separated. Unlike the electromagnetic force which diminishes as charged particles separate, color charged particles feel increasing force; effectively, they can never separate from one another.

However, color charged particles may combine to form color neutral composite particles called hadrons. A quark may pair up to an antiquark: the quark has a color and the antiquark has the corresponding anticolor. The color and anticolor cancel out, forming a color neutral meson. Or three quarks can exist together: one quark is "red", another "blue", another "green". These three colored quarks together form a color neutral baryon. Or three antiquarks can exist together: one antiquark is "antired", another "antiblue", another "antigreen". These three anticolored antiquarks form a color neutral antibaryon.

Quarks also carry fractional electric charges, but since they are confined within hadrons whose charges are all integral, fractional charges have never been isolated. Note that quarks have electric charges of either +2/3 or 1/3, whereas antiquarks have corresponding electric charges of either 2/3 or +1/3.

Evidence for the existence of quarks comes from deep inelastic scattering: firing electrons at nuclei to determine the distribution of charge within nucleons (which are baryons). If the charge is uniform, the electric field around the proton should be uniform and the electron should scatter elastically. Low-energy electrons do scatter in this way, but above a particular energy, the protons deflect some electrons through large angles. The recoiling electron has much less energy and a jet of particles is emitted. This inelastic scattering suggests that the charge in the proton is not uniform but split among smaller charged particles: quarks.

Fundamental bosons

Main article: boson

In the Standard Model, vector (spin-1) bosons (gluons, photons, and the W and Z bosons) mediate forces, while the Higgs boson (spin-0) is responsible for particles having intrinsic mass.

Gluons

Main article: gluon

Gluons are the mediators of the strong interaction and carry both color and anticolor. Although gluons are massless, they are never observed in detectors due to confinement;

rather, they produce jets of hadrons, similar to single quarks. The first evidence for gluons came from annihilations of electrons and positrons at high energies which sometimes produced three jets - a quark, an antiquark, and a gluon.

Electroweak bosons

Main article: W and Z bosons

There are three weak gauge bosons: W^+, W, and Z^0; these mediate the weak interaction. The massless photon mediates the electromagnetic interaction.

Higgs boson

Although the weak and electromagnetic forces appear quite different to us at everyday energies, the two forces are theorized to unify as a single electroweak force at high energies. This prediction was clearly confirmed by measurements of cross-sections for high-energy electron-proton scattering at the HERA collider at DESY. The differences at low energies is a consequence of the high masses of the W and Z bosons, which in turn are a consequence of the Higgs mechanism. Through the process of spontaneous symmetry breaking, the Higgs selects a special direction in electroweak space that causes three electroweak particles to become very heavy (the weak bosons) and one to remain massless (the photon). Although the Higgs mechanism has become an accepted part of the Standard Model, the Higgs boson itself has not yet been observed in detectors. Indirect evidence for the Higgs boson suggests its mass lies below about 200 GeV. In this case, the LHC experiments will be able to discover this last missing piece of the Standard Model.

Beyond the Standard Model

Although all experimental evidence confirms the predictions of the Standard Model, many physicists find this model to be unsatisfactory due to its many undetermined parameters, many fundamental particles, the non-observation of the Higgs boson and other more theoretical considerations such as the hierarchy problem. There are many speculative theories beyond the Standard Model which attempt to rectify these deficiencies.

Grand unification

Main article: grand unification theory

One extension of the Standard Model attempts to combine the electroweak interaction with the strong interaction into a single 'grand unified theory' (GUT). Such a force would be spontaneously broken into the three forces by a Higgs-like mechanism. The most dramatic prediction of grand unification is the existence of X bosons, which cause proton decay. However, the non-observation of proton decay at Super-Kamiokande rules out the simplest GUTs, including SU(5) and SO(10).

Supersymmetry

Main article: supersymmetry

Supersymmetry extends the Standard Model by adding an additional class of symmetries to the Lagrangian. These symmetries exchange fermionic particles with bosonic ones. Such a symmetry predicts the existence of supersymmetric particles, abbreviated as sparticles, which include the sleptons, squarks, neutralinos and charginos. Each particle in the Standard Model would have a superpartner whose spin differs by 1/2 from the ordinary particle. Due to the breaking of supersymmetry, the sparticles are much heavier than their ordinary counterparts; they are so heavy that existing particle colliders would not be powerful enough to produce them. However, some physicists believe that sparticles will be detected when the Large Hadron Collider at CERN begins running.

String theory

According to string theorists, each kind of fundamental particle corresponds to a different patterns of fundamental string. All strings are essentially the same, although they may be open (lines) or closed (loops). Different particles differ in the coordination of their strings. Modern string theories include supersymmetry, making them superstring theories. One particular prediction of string theory is the existence of extremely massive counterparts of ordinary particles due to vibrational excitations of the fundamental string. Another important prediction of string theory is the existence of a massless spin-2 particle behaving like the graviton. By predicting gravity, string theory unifies quantum mechanics with general relativity, making it the first consistent theory of quantum gravity. One problem with string theory is that it predicts that the number of dimensions for spacetime much greater than 4 (the number of observed dimensions). These extra dimensions are supposedly compactified or rolled-up. Other related theories such as brane theories contain extended extra dimensions, which are hidden from us by our confinement to a brane.

Preon theory

According to preon theory there are one or more orders of particles more fundamental than those (or most of those) found in the Standard Model. The most fundamental of these are normally called preons, which is derived from "pre-quarks". In essence, preon theory tries to do for the Standard Model what the Standard Model did for the particle zoo that came before it. Most models assume that almost everything in the Standard Model can be explained in terms of three to half a dozen more fundamental particles and the rules that govern their interactions. Interest in preons has waned since the simplest models were experimentally ruled out in the 1980's.

Links and References

Reference

- Brian Greene, *The Elegant Universe*, W.W.Norton & Company, 1999, ISBN 0-393-05858-1.

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Atom

An **atom** is the smallest, irreducible constituent of a chemical system. The word is derived from the Greek *atomos*, indivisible, from *a*-, not, and *tomos*, a cut. It usually means chemical atoms, the basic constituents of molecules and ordinary matter. These atoms are not divisible by chemical reactions but are now known to be composed of even smaller subatomic particles. The sizes of these atoms are generally in the range from 10 pm to 100 pm. This article discusses these chemical atom(s).

The variety of matter that is dealt with in everyday experience consists of discrete atoms. The existence of such particles was first proposed by Greek philosophers such as Democritus, Leucippus, and the Epicureans, but without any real way to be sure, the concept disappeared until it was revived by Rudjer Boscovich in the 18th century, and after that applied to chemistry by John Dalton.

Rudjer Boscovich based his theory on Newtonian mechanics and published it in 1758 within his *Theoria philosophiae naturalis redacta ad unicam legem virium in natura existentium*. According to Boscovich, atoms are stuctureless points, which exhibit repelling and attracting forces on each other, depending on distance. John Dalton used the atomic theory to explain why gases always combine in simple ratios. It was with Amedeo Avogadro's work, in the 19th century, that scientists began to distinguish atoms and molecules. In modern times atoms have been observed experimentally.

As it turns out, atoms are themselves made out of smaller particles. In fact, almost all of an atom is empty space. At the center is a tiny positive nucleus composed of nucleons (protons and neutrons), and the rest of the atom contains only the fairly flexible electron shells. Usually atoms are electrically neutral with as many electrons as protons. Atoms are generally classified by the atomic number, which corresponds to the number of protons in the atom. For example, carbon atoms are those atoms containing 6 protons. All atoms with the same atomic number share a wide variety of physical properties and exhibit the same chemical behavior. The various kinds of atoms are listed in the Periodic table. Atoms having the same atomic number, but different atomic masses (due to their different numbers of neutrons), are called isotopes.

The simplest atom is the hydrogen atom, having atomic number 1 and consisting of one proton and one electron. It has been the subject of much interest in science, particularly in the early development of quantum theory.

The chemical behavior of atoms is largely due to interactions between the electrons. In particular the electrons in the outermost shell, called the valence electrons, have the greatest influence on chemical behavior. Core electrons (those not in the outer shell) play a role, but it is usually in terms of a secondary effect due to screening of the positive charge in the atomic nucleus.

There is a strong tendency for atoms to completely fill (or empty) the outer electron shell, which in hydrogen and helium has space for two electrons, and in all other atoms has space for eight. This is achieved either by sharing electrons with neighboring atoms or by completely removing electrons from other atoms. When electrons are shared a covalent bond is formed between the two atoms. Covalent bonds are the strongest type of atomic bond.

When one or more electrons are completely removed from one atom by another, ions are formed. Ions are atoms that possess a net charge due to an imbalance in the number of protons and electrons. The ion that stole the electron(s) is called an *anion* and is negatively charged. The atom that lost the electron(s) is called a *cation* and is positively charged. Cations and anions are attracted to each other due to coulombic forces between the positive and negative charges. This attraction is called ionic bonding and is weaker than covalent bonding.

As mentioned above covalent bonding implies a state in which electrons are shared equally between atoms, while ionic bonding implies that the electrons are completely confined to the anion. Except for a limited number of extreme cases, neither of these pictures is completely accurate. In most cases of covalent bonding, the electron is unequally shared, spending more time around the more electronegative atom, resulting in the covalent bond having some ionic character. Similarly, in ionic bonding the electrons often spend a small fraction of time around the more electropositive atom, resulting in some covalent character for the ionic bond.

Models of the atom

- Democritus' shaped-atom model (for want of a better name)
- The plum pudding model
- The Bohr model
- The quantum mechanical model

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Atomic nucleus

The center of an atom is called the **nucleus**. It is composed of one or more protons and usually some neutrons as well. The number of protons in an atom's nucleus is called the atomic number, and determines which element the atom is (for example hydrogen, carbon, oxygen, etc.).

Though the positively charged protons exert a repulsive electromagnetic force on each other, the distances between nuclear particles are small enough that the strong interaction

(which is stronger than the electromagnetic force but decreases more rapidly with distance) predominates. (The gravitational attraction is negligible, being a factor 10^{36} weaker than this electromagnetic repulsion.)

The discovery of the electron was the first indication that the atom had internal structure. This structure was initially imagined according to the "raisin cookie" or "plum pudding" model, in which the small, negatively charged electrons were embedded in a large sphere containing all the positive charge. Ernest_Rutherford and Marsden, however, discovered in 1911 that alpha particles from a radium source were sometimes scattered backwards from a gold foil, which led to the acceptance of a planetary model, in which the electrons orbited a tiny nucleus in the same way that the planets orbit the sun.

A heavy nucleus can contain hundreds of nucleons (neutrons and protons), which means that to some approximation it can be treated as a classical system, rather than a quantum-mechanical one. In the resulting liquid-drop model, the nucleus has an energy which arises partly from surface tension and partly from electrical repulsion of the protons. The liquid-drop model is able to reproduce many features of nuclei, including the general trend of binding energy with respect to mass number, as well as the phenomenon of nuclear fission.

Superimposed on this classical picture, however, are quantum-mechanical effects, which can be described using the nuclear shell model, developed in large part by Maria Goeppert-Mayer. Nuclei with certain numbers of neutrons and protons (the magic numbers 2, 8, 20, 50, 82, 126, ...) are particularly stable, because their shells are filled.

Since some nuclei are more stable than others, it follows that energy can be released by nuclear reactions. The sun is powered by nuclear fusion, in which two nuclei collide and merge to form a larger nucleus. The opposite process is fission, which powers nuclear power plants. Because the binding energy per nucleon is at a maximum for medium-mass nuclei (around iron), energy is released either by fusing light nuclei or by fissioning heavier ones.

The elements up to iron are created in a star during a series of fusion stages. First hydrogen fuses with itself to form helium, then helium fuses with itself twice to make carbon, and further fusings proceed to make heavier elements, until the series of fusions make iron which will not fuse further. If the star explodes in a supernova, the high energy neutrinos streaming from the supernova will bombard the escaping elements to form substantial portions of the elemental neuclei heavier than iron. Hence, during stellar evolution through the progression of stages in fusing succeedingly heavier elements, the death of a star in a supernova can create the elements necessary for life.

Nuclear reactions occur naturally on earth. Except in manmade conditions, such as atomic explosions, temperatures and pressures on earth are not high enough to overcome the electrical repulsion between nuclei and allow fusion. But heavy nuclei such as uranium may undergo fission and alpha decay, and beta decay can also occur. Alpha decay can be considered as an extremely asymmetric case of fission, in which one fragment is a helium nucleus (alpha particle). In beta decay, either a proton is converted into a neutron (with the emission of an antielectron and a neutrino) or a neutron is converted into a proton (emitting an electron and an antineutrino).

Much of current research in nuclear physics relates to the study of nuclei under extreme conditions. The heaviest of all nuclei are neutron stars. Nuclei may also be characterized by extreme shapes (like footballs) or by extreme neutron-to-proton ratios. Experimenters can also use artificially induced fusion at high energies to create nuclei at very high

temperatures, and there are signs that these experiments have produced a phase transition from normal nuclear matter to a new state, the quark-gluon plasma, in which the quarks mingle with one another, rather than being segregated in triplets as neutrons and protons.

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Proton

In physics, the **proton** is a subatomic particle with a positive fundamental electric charge of 1.6×10^{-19} coulomb, a mass of 938 MeV ($1.6726231 \times 10^{-27}$ kg, or about 1800 times that of an electron) and a half-life of about 10^{33} years. The nucleus of the most common isotope of the hydrogen atom, H, is a single proton. The nuclei of other atoms are composed of neutrons and protons held together by the strong nuclear force. The number of protons in the nucleus determines the chemical properties of the atom and what chemical element it is.

Protons are classified as baryons and are composed of two up quarks and one down quark, which are also held together by the strong nuclear force, mediated by gluons.

Because the electromagnetic force is many orders of magnitude stronger than the gravitational force, the charge on the proton must be equal to the charge on the electron, otherwise the net repulsion of having an excess of positive or negative charge (depending on which charge was numerically greater - atoms would not be electrically neutral) would cause a noticeable expansion effect on the universe, and indeed any gravitationally aggregated matter (planets, stars, etc.). It is taken that the positron (antielectron) has the same magnitude charge as the electron but opposite in sign; the same applies for the antiproton and proton.

In chemistry and biochemistry, the term proton may refer to the hydrogen ion in aqueous solution (in other words, the hydronium ion). In this context, a proton donor is an acid and a proton acceptor a base (see acid-base reaction theories).

See also: particle physics, neutron

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Neutron

In physics, the **neutron** is a subatomic particle with no net electric charge and a mass of 940 MeV (very slightly more than a proton). The nucleus of most atoms (all except the most common isotope of Hydrogen, which consists of a single proton only) consists of protons and neutrons. Outside the nucleus, neutrons are unstable and have a half-life of about 15 minutes, decaying by emitting an electron and antineutrino to become a proton. The same decay method (beta decay) occurs in some nuclei. Particles inside the nucleus are typically resonances between neutrons and protons, which transform into one another by the emission and absorption of pions. A neutron is classified as a baryon, and consists of two down quarks and one up quark.

The characteristic of neutrons which most differentiates them from other common subatomic particles is the fact that they are uncharged. This property of neutrons delayed their discovery, makes them very penetrating, makes it impossible to observe them directly, and makes them very important as agents in nuclear change.

Although atoms in their normal state are also uncharged, they are ten thousand times larger than a neutron and consist of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (such as gamma rays) lose energy in passing through matter. They exert electric forces which ionize atoms of the material through which they pass. The energy taken up in ionization equals the energy lost by the charged particle, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by the very short-range strong nuclear force which comes into play when the neutron comes very close indeed to an atomic nucleus. Consequently a free neutron goes on its way unchecked until it makes a "head-on" collision with an atomic nucleus. Since nuclei have a very small cross section, such collisions occur but rarely and the neutron travels a long way before colliding.

In the case of a collision of the elastic type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it acquires relatively little speed, but if it is a proton, which is approximately equal in mass to the neutron, it is projected forward with a large fraction of the original speed of the neutron, which is itself correspondingly slowed. Secondary projectiles resulting from these collisions may be detected, for they are charged and produce ionization.

The uncharged nature of the neutron makes it not only difficult to detect but difficult to control. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields which have no effect on neutrons. Furthermore, free neutrons can be obtained only from nuclear disintegrations; there is no natural supply. The only means we have of controlling free neutrons is to put nuclei in their way so that they will be slowed and deflected or absorbed by collisions. These effects are of great practical importance in nuclear reactors and nuclear weapons.

Discovery

In 1930 Walther Bothe and H. Becker in Germany found that if the very energetic natural alpha particles from polonium fell on certain of the light elements, specifically beryllium, boron, or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) the physicist James Chadwick in England performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that in fact the new radiation consisted of uncharged particles of approximately the mass of

the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

Current developments

The existence of stable clusters of four neutrons, or tetraneutrons, has been hypothesised by a team led by Francisco-Miguel Marqués at the CNRS Laboratory for Nuclear Physics based on observations of the disintegration of beryllium-14 nuclei. This is particularly interesting, because current theory suggests that these clusters should not be stable, and therefore not exist.

See also particle physics

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Electron

The **electron** is a subatomic particle. It has a negative electric charge of -1.6×10^{-19} coulombs, and a mass of about 9.10×10^{-31} kg (0.51 MeV/c^2).

The electron is commonly represented as $\mathbf{e}^-$. The antiparticle of the electron is the positron, which is identical to an electron but has positive electrical charge.

Atoms consist of a nucleus of protons and neutrons surrounded by electrons. Electrons are very light compared to the other two types of particles: a proton is about 1800 times as heavy as an electron.

The electron is one of a class of subatomic particles called leptons which are believed to be fundamental particles (that is, they cannot be broken down into smaller constituent parts). The electron has spin 1/2, which implies it is a fermion, i.e., follows the Fermi-Dirac statistics.

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History

The electron had been posited by G. Johnstone Stoney, as a unit of charge in electrochemistry, but Thompson realised that it was also a subatomic particle.

The electron was discovered by J.J. Thomson in 1897 at the Cavendish Laboratory at Cambridge University, while studying "cathode rays." Influenced by the work of James Clerk Maxwell, and the discovery of the X-ray, he deduced that cathode rays existed and were negatively charged "*particles*", which he called "*corpuscles*".

Technical details

The electron is described in quantum mechanics by the Dirac Equation.

In the Standard Model it forms a doublet in SU(2) with the electron neutrino, as they interact through the weak interaction. The electron has two more massive partners, with the same charge but different masses: the muon and the tau.

Electricity

When electrons move, free of the nuclei of atoms, and there is a net flow, this flow is called electricity, or an electric current. This might be compared to a flock of sheep moving north together, while the shepherds do not. Electric charge can be directly measured with an electrometer. Electric current can be directly measured with a galvanometer.

So-called "static electricity" is not a flow of electrons at all. More correctly called a "static charge", it refers to a body that has more or fewer electrons than are required to balance the positive charge of the nuclei. When there is an excess of electrons, the object is said to be "negatively charged". When there are fewer electrons than protons, the object is said to be "positively charged". When the number of electrons and the number of protons are equal, the object is said to be electrically "neutral".

See also

- Standard model
- Proton
- Neutron

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Quark

In particle physics, the **quarks** are one of the two families of subatomic particles thought to be elemental and indivisible (the other being the leptons). Objects made up of quarks are known as hadrons; well known examples are protons and neutrons.

Quarks are generally believed to never exist alone but only in groups of two or three (and, more recently, five); all searches for free quarks since 1977 have yielded negative results. Quarks are differentiated from leptons, the other family of elemental particles, by electric charge. Leptons (such as the electron or the muon) have integral charge (+1, 0 or -1) while quarks have +2/3 or -1/3 charge (antiquarks have -2/3 or +1/3 charge). All quarks have spin 1/2 $\hbar$.

Six different quarks are known; search for *4th-generation quarks* is underway. The known quarks are:

Name	Charge	Estimated mass (MeV)
Up (u)	+2/3	1.5 to 4.5 [1]
Down (d)	-1/3	5 to 8.5 [1]
Charm / Centre (c)	+2/3	1,000 to 1,400
Strange / Sideways (s)	-1/3	80 to 155
Top / Truth (t)	+2/3	174,300 ± 5,100
Bottom / Beauty (b)	-1/3	4,000 to 4,500

1. The estimates of u and d masses are not uncontroversial and still actively being investigated; in fact, there are even suggestions in literature that the u quark could be essentially massless.

Ordinary matter such as protons and neutrons are composed of quarks of the UP or DOWN variety only. A proton contains two UP quarks and one DOWN quark, giving a total charge of +1. A neutron is made of two DOWN quarks and one UP quark, giving a total charge of zero. The other varieties of quarks can only be produced in particle accelerators, and degenerate quickly to the UP and DOWN quarks. (Electrons do not contain quarks, but are of a different type of particle called a Lepton).

According to the theory of quantum chromodynamics (QCD), quarks possess another property that is called "color charge" (and that doesn't have anything to do with real color). Instead of just two different charge types (like + and - in electromagnetism), color charge comes in 3 types: "red", "green" and "blue" (6 if we count the "anticharges"). In the theory, only "color neutral" particles can exist. Particles composed of one red, one green and one blue quark are called baryons; the proton and the neutron are the most important examples. Particles composed of a quark and an anti-quark of the corresponding anti-color are called mesons.

Particles of different color charge are attracted and particles of like color charge are repelled by the strong nuclear force, which is transferred by gluons, particles that themselves carry color charge. Therefore, colors of quarks are not static, but are interchanged by gluons, always maintaining the result neutral. This interchange of color charge is thought to result in the strong nuclear force holding quarks together in mesons and baryons; a "secondary" effect of this strong nuclear force is to hold the protons and neutrons together in the atomic nucleus.

Due to the extremely strong nature of the strong force, quarks are never found free. They are always bound into baryons or mesons. When we try to separate quarks in a meson or

baryon, as happens in particle accelerators, the strong force actually becomes stronger as they get farther apart. At some point it is more energetically favorable to create two more quarks to cancel out the increasing force, and two new quarks (a quark and an anti-quark) pop out of the vacuum. This process is called hadronization or fragmentation, and is one of the least understood processes in particle physics. As a result of fragmentation, when quarks are produced in particle accelerators, instead of seeing the individual quarks in detectors, scientists see "jets" of many color-neutral particles (mesons and baryons), clustered together.

The theory behind quarks was first suggested by physicists Murray Gell-Mann and George Zweig, who found they could explain the properties of many particles by considering them to be composed of these elementary quarks. The name quark comes from "three quarks for Muster Mark", a nonsense phrase in James Joyce's *Finnegans Wake.*

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Photon

In physics, a **photon** is a quantum of excitation of the quantised electromagnetic field. It is considered one of the elementary particles of the Standard Model.

It is usually given the symbol ^{3} (gamma) although in high energy physics this refers to high energy photons (photons of the immediately lower energy branch for instance are noted *X* and called *X* rays).

Photons are often loosely associated to light, to which they relate only for a very narrow frequency window of the spectrum. Even there, light is commonly encountered in quantum states which are not pure photons but superpositions of different numbers of photons, to wit, either coherent superpositions (so-called coherent states) describing coherent light such as the one emitted by an ideal laser, or chaotic superpositions (so-called thermal states) describing light in thermal equilibrium (blackbody radiation). Special devices like micromasers can create pure photon type of light. The associated quantum state is the Fock state denoted |*n*>, meaning *n* photons in the electromagnectic field mode understood. If the field is multimode, its quantum state is a tensor product of photon states, e.g.,

$$|n_{k_0}\rangle \otimes |n_{k_1}\rangle \otimes \ldots \otimes |n_{k_n}\rangle \ldots$$

with k_i the possible momenta of the modes and n_{k_i} the number of photons in this mode.

Photons can be produced in a variety of ways, including emission from electrons as they change energy states or orbitals. They can also be created by nuclear transitions, particle-antiparticle annihilation or any fluctuations in an electromagnetic field.

In a vacuum, photons move at the speed of light *c*, defined equal to 299,792,458 m/s (this is a definition and hence does not suffer any experimental uncertainty), or about $3x10^8$ m/s. The dispersion relation is linear and the constant of proportionality is Planck's constant *h*, yielding the useful relations for kinematic studies, *E* = *h* ½ (with *E* the photon energy and ½ the frequency of the mode, or photon frequency) and *p* = *h* ½ / *c* (*p* the momentum). Photons are believed to be fundamental particles. Their lifetime is infinite. Their spin is 1 and they are therefore bosons. However since they travel at the speed of light, they have only two spin

projections, since the zero projection requires a frame where the photon is still. Such a frame does not exist according to the theory of relativity. They have zero invariant mass but a definite finite energy at the speed of light. Even so, the theory of general relativity states that they are affected by gravity, and this is confirmed by observation.

In a material, they couple to the excitations of the media and behave differently. For instance when they couple to phonons or excitons they give rise to polaritons. Their dispersion departs from the straight line and they acquire an effective mass. Therefore their speed gets lower than the speed of light.

see also

- particle physics

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Gluon

In physics, **gluons** are the elementary particles which are responsible for the strong nuclear force. They bind quarks together to form protons and neutrons; their electric charge is zero, their spin is 1 and they are generally assumed to have zero mass. Gluons are ultimately responsible for the stability of atomic nuclei.

In quantum chromodynamics (QCD), today's accepted theory for the description of the strong nuclear force, gluons are exchanged when particles with a color charge interact. When two quarks exchange a gluon, their color charges change; the gluon carries an anti-color charge to compensate for the quark's old color charge, as well as the quark's new color charge. Since gluons thus carry a color-charge themselves, they can also interact with other gluons, which makes the mathematical analysis of the strong nuclear force quite complicated and difficult.

The first experimental traces of gluons were found in the early 1980s at the electron-positron-collider PETRA at the DESY in Hamburg, when evidence for a clear three-jet structure was found; the third jet was attributed to one of the produced quarks emitting a gluon.

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W and Z bosons

The **W boson** is an elementary particle, having an electric charge of just ±1, a mass of 80.4110 GeV (about 80 times the proton's mass), and weak isospin of the same. There exist three varieties of W bosons: positively-charged types, negatively-charged (antiparticles of each other) types, and the **Z boson**, which possesses no charge whatsoever. The discovery of the W Boson occurred in 1983, during a series of SPS accelerator-based experiments being

conducted by Carlo Rubbia and Simon Van der Meer, working at the CERN laboratory. For their efforts, they were awarded the Nobel Prize, one year later.

W and Z bosons mediate the weak nuclear force. The W Boson is best known for mediating reactions for nuclear decay (fission). For example

n ’ p + e + ½$_e$

(neutron decays into proton + electron + anti-neutrino). This reaction is known as beta decay. The opposite process also occurs:

p + e ’ n + ½$_e$

(proton + electron goes to neutron + neutrino) and is called electron capture. Since protons are not fundamental particles (they are made up of quarks), it is the quarks that interact. The first example is then

d ’ W + u,

and then the W decays into an electron and electron-type neutrino.

That the W and Z bosons have mass is something of a conundrum. The W and Z are accurately described by a SU(2)xU(1) Gauge theory, but the bosons in a gauge theory must be massless. The photon is also massless because the photon and electromagnetism are described by a U(1) gauge theory. Some mechanism is required to break the SU(2) symmetry, giving mass to the W and Z in the process. The most popular is called the Higgs mechanism, and requires an extra particle, the Higgs Boson.

The combination of the SU(2) gauge theory describing the W and Z, the electromagnetic interaction, and the Higgs mechanism is known as the Glashow-Weinberg-Salam model. Glashow, Weinberg, and Salam won the 1979 Nobel Prize in Physics for this work. These days it is very widely accepted, and has been adopted as part of the standard model of particle physics. At the present time (Sep 25, 2001), the only missing piece of this model is the Higgs Boson.

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Graviton

In physics, the **graviton** is a hypothetical elementary particle that transmits the force of gravity in most quantum gravity systems. In order to do this gravitons have to be always-attractive (gravity never pushes), work over any distance (gravity is universal) and come in unlimited numbers (to provide high strengths near stars). In a quantum theory this defines an even-spin (spin 2 in this case) boson with a rest mass of zero.

Gravitons are postulated simply because quantum has been so successful in other fields. For instance, electrodynamics can be very well explained by the application of quantization to photons. In this case photons are being continually created and destroyed by all charged particles, and the interactions between these photons produce the macroscopic forces we are familiar with, like magnetism.

Given the widespread success of quantum in describing the vast majority of basic forces in the universe, it seemed only natural that the same methods would work well on gravity as well. Many attempts were made to introduce a so-far unseen graviton, which would work in

a fashion somewhat similar to the photon. It was hoped that this would quickly lead to a quantum gravity theory, although the math was a bit difficult.

It has not worked out that way. Any such theory would require a graviton to operate in a fashion similar to a photon, but unlike electrodynamics where the photons act directly on each other and their charged particles, gravity just doesn't work so simply. Well-observed behaviours show that gravity is created by any form of energy (mass simply being a particularily condensed form), which is difficult to describe in a fashion similar to "charge". To date all attempts to create a consistent simple quantum gravity theory have failed.

Detecting a graviton, if it exists, would prove rather problematic. The particles carry very little energy[1] so detecting them would be very difficult. The only way to detect them would be to look for cases where the overall motion or energy of an object changes in a way that is different than predicted by general relativity, but one of the basic principles of quantum gravity would be that it matches those predictions as closely as possible.

It should be noted that a quantum gravity theory does not require a graviton; for instance, loop quantum gravity has no analogous particle.

Notes:

1) Many people are surprised to learn that gravity is the weakest force. A simple experiment will demonstrate this, however: lift your arm. You have now lifted several kilograms of mass against the gravity generated by the entire planet.

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Neutrino

The **neutrino** is an elementary particle. It has spin 1/2 and so it is a fermion. Its mass is very small, though recent experiments (see Super-Kamiokande) have shown it to be different from zero. It only interacts through the weak interaction and feels neither the strong nor the electromagnetic interaction(but it feels gravity, since it has a mass, but since it is extremely small, when gravity is already the weakest force, it hardly matters).

Because the neutrino only interacts weakly, when moving through ordinary matter its chance of interacting with it is very small. It would take a light year of lead to block half the neutrinos flowing through it. Neutrino detectors therefore typically contain hundreds of tons of a material constructed so that a few atoms per day would interact with the incoming neutrinos. In collapsing supernova, the densities at the core become high enough (10^{14} grams / cc) that the produced neutrinos can be detected.

There are three different kinds, or *flavors*, of neutrinos: the electron neutrino ½e, the muon neutrino ½¼ and the tau neutrino ½Ä, named after their partner lepton in the Standard Model.

The neutrino was first postulated by Wolfgang Pauli to explain the continuous spectrum of the beta decay.

Massive neutrinos can oscillate between the three flavors, in a phenomenon known as neutrino oscillation (which provides a solution to the solar neutrino problem and the atmospheric neutrino problem at the same time).

Most of the energy of a collapsing supernova is radiated away on the form of neutrinos which are produced when protons and electrons in the core combine to form neutrons. This produces an inmense burst of neutrinos. The first experimental evidence came in the year 1987, when neutrinos coming from the supernova 1987a were detected.

Some years ago it was believed that massive neutrinos could account for the dark matter, though with the current knowledge of neutrino masses they don't contribute a significant fraction to it. Cosmological observations provide themselves limits on the properties of the neutrino.

Neutrino detectors

There are several types of neutrino detectors. Each type consists of a large amount of material in an underground cave designed to shield it from cosmic radiation.

- Chlorine detectors were the first used and consist of a tank filled with dry cleaning fluid. In these detectors a neutrino would convert a chlorine atom into one of argon. The fluid would periodically be purged with helium gas which would remove the argon. The helium would then be cooled to separate out the argon. These detectors had the failing that it was impossible to determine the direction of the incoming neutron. It was the chlorine detector in Homestake, South Dakota, containing 520 tons of fluid, which first detected the deficit of neutrinos from the sun that led to the solar neutrino problem. This type of detector is only sensitive to ½$_{e}$.
- Gallium detectors are similar to chlorine detectors but more sensitive to low-energy neutrinos. A neutrino would convert gallium to germanium which could then be chemically detected. Again, this type of detector provides no information on the direction of the neutrino.
- Pure water detectors such as Super-Kamiokande contain a large area of pure water surrounded by sensitive light detectors known as photomultiplier tubes. In this detector, the neutrino transfers its energy to an electron which then travels faster than the speed of light in the medium (though slower than the speed of light in a vacuum). This generates an "optical shockwave" known as Cherenkov radiation which can be detected by the photomultiplier tubes. This detector has the advantage that the neutrino is recorded as soon as it enters the detector, and information about the direction of the neutrino can be gathered. It was this type of detector that recorded the neutrino burst from Supernova 1987a. This type of detector is sensitive to ½$_{e}$ and ½$_{¼}$.
- Heavy water detectors use three types of reactions to detect the neutrino. The first is the same reaction as pure water detectors. The second involves the neutrino striking the deuterium atom releasing an electron. The third involves the neutrino breaking the deuterium atom into two. The results of these reactions can be detected by photomultiplier tubes. This type of detector is in operation in the Sudbury Neutrino Observatory. This type of detector is sensitive to all three neutrino flavors.

See also particle physics.

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Particle radiation

Particle radiation refers to the radiation of energy by means of small fast moving particles that have energy and mass.

Particle radiation can be emitted from an unstable atomic nucleus (radioactive decay) in the form of a positively charged Alpha particle (±), a positively or negatively charged (the latter being more common) Beta particle([2]),a neutron, or Gamma rays ([3]). Gamma rays are a form of electromagnetic radiation, but exhibit particle-like properties (see photon) due to their high energy. Other forms of particle radiation include neutrons, positrons and neutrinos.

Cosmic rays are subatomic particles falling naturally on the Earth. Most originate in the Sun and are part of the solar wind.

Radiation is often separated into two categories, *ionizing* and *non-ionizing*, to denote the energy and danger of the radiation. Ionization is the process of removing electrons from atoms, leaving two electrically charged particles (ions) behind. Some forms of radiation like visible light, microwaves, or radio waves do not have sufficient energy to remove electrons from atoms and hence, are called non-ionizing radiation. The negatively charged electrons and positively charged nuclei created by ionizing radiation may cause damage in living tissue. The term *radioactivity* generally refers to the release of ionizing radiation.

see physics, nuclear physics

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Phonon

A **phonon** is a quantized mode of vibration occurring in a rigid crystal lattice, such as the atomic lattice of a solid. The study of phonons is an important part of solid state physics, because they contribute to many of the physical properties of materials, such as thermal and electrical conductivity. For example, the propagation of phonons is responsible for the conduction of heat in insulators, and the properties of long-wavelength phonons gives rise to sound in solids (hence the term *phonon*; phonons are phonic).

According to a well-known result in classical mechanics, any vibration of a lattice can be decomposed into a superposition of normal modes of vibration. When these modes are analysed using quantum mechanics, they are found to possess some particle-like properties (see wave-particle duality.) When treated as particles, phonons are bosons possessing zero spin.

The following article provides an overview of the physics of phonons.

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Non-interacting phonons

Modelling a lattice

We begin our investigation of phonons by examining the mechanical systems from which they emerge. Consider a rigid regular (or "crystalline") lattice composed of *N* particles. We will refer to these particles as "atoms", though in a real solid they may actually be ions. *N* is some large number, say around 10^{23} (Avogadro's number) for a typical piece of solid.

If the lattice is rigid, the atoms must be exerting forces on one another, so as to keep each atom near its equilibrium position. In real solids, these forces include Van der Waals forces, covalent bonds, and so forth, all of which are ultimately due to the electric force; magnetic and gravitational forces are generally negligible. The forces between each pair of atoms may be characterized by some potential energy function *V*, depending on the separation of the atoms. The potential energy of the *entire* lattice is the sum of all the pairwise potential energies:

$$\sum_{i \neq j} V(r_i - r_j)$$

where r_i is the position of the *i*th atom, and *V* is the potential energy between two atoms.

It is extremely difficult to solve this many-body problem in full generality, in either classical or quantum mechanics. In order to simplify the task, we introduce two important approximations. Firstly, we only perform the sum over neighbouring atoms. Although the electric forces in real solids extend to infinity, this approximation is nevertheles valid because the fields produced by distant atoms are screened. Secondly, we treat the potentials *V* as harmonic potentials, which is permissible as long as the atoms remain close to their equilibrium positions. (Formally, this is done by Taylor expanding *V* about its equilibrium value.)

The resulting lattice may be visualized as a system of balls connected by springs. Two such lattices are shown in the figures below. The figure on the left shows a cubic lattice, which is a good model for many types of crystalline solid. The figure on the right shows a

linear chain, a very simple lattice which we will shortly use for modelling phonons. Other common lattices may be found in the article on crystal structure.

The potential energy of the lattice may now be written as

$$\sum_{i \neq j(nn)} \frac{1}{2} m\omega^2 (R_i - R_j)^2$$

Here, É is the natural frequency of the harmonic potentials, which we assume to be the same since the lattice is regular. R_i is the position coordinate of the *i*th atom, which we now measure from its *equilibrium* position. The sum over nearest neighbours is denoted as "*(nn*".

Lattice waves

Due to the connections between atoms, the displacement of one or more atoms from their equilibrium positions will give rise to a set of vibration waves propagating through the lattice. One such wave is shown in the figure below. The amplitude of the wave is given by the displacements of the atoms from their equilibrium positions. The wavelength » is marked.

It should be noted that there is a minimum possible wavelength, given by the equilibrium separation *a* between atoms. As we shall see in the following sections, any wavelength shorter than this can be mapped onto a wavelength longer than *a*.

Not every possible lattice vibration has a well-defined wavelength and frequency. However, the normal modes (which, as we mentioned in the introduction, are the elementary building-blocks of lattice vibrations) do possess well-defined wavelengths and frequencies. We will now examine these normal modes in some detail.

One-dimensional phonons

We begin by studying the simplest model of phonons, a one-dimensional quantum mechanical harmonic chain. The formalism for this one-dimensional model is readily generalizable to two and three dimensions. Consider a linear chain of *N* atoms. The Hamiltonian for this system is

$$\mathbf{H} = \sum_{i=1}^{N} \frac{p_i^2}{2m} + \frac{1}{2} m\omega^2 \sum_{\{ij\}(nn)} (x_i - x_j)^2$$

where *m* is the mass of each atom, and x_i and p_i are the position and momentum operators for the *i*th atom. A discussion of similar Hamiltonians may be found in the article on the quantum harmonic oscillator.

We introduce a set of *N* "normal coordinates" Q_k, defined as the discrete Fourier transforms of the *x*'s, and *N* "conjugate momenta" defined as the Fourier transforms of the *p*'s:

$$\begin{aligned} x_j &= \tfrac{1}{\sqrt{N}} \textstyle\sum_k Q_k e^{ikja} \\ p_j &= \tfrac{1}{\sqrt{N}} \textstyle\sum_k \Pi_k e^{-ikja} \end{aligned}$$

The quantity *k* will turn out to be the wave number of the phonon, i.e. *2À* divided by the wavelength. It takes on quantized values, because the number of atoms is finite. The form of

the quantization depends on the choice of boundary conditions; for simplicity, we impose *periodic* boundary conditions, defining the *(N+1)*th atom as equivalent to the first atom. Physically, this corresponds to joining the chain at its ends. The resulting quantization is

$$k = \frac{2n\pi}{Na} \quad \text{for } n = 0, \pm 1, \pm 2, \ldots \pm N$$

The upper bound to *n* comes from the minimum wavelength imposed by the lattice spacing *a*, as discussed above.

By inverting the discrete Fourier transforms to express the *Q*'s in terms of the *x*'s and the 's in terms of the *p*'s, and using the canonical commutation relations between the *x*'s and *p*'s, we can show that

$$[Q_k, \Pi_{k'}] = i\hbar\delta_{kk'} \quad ; \quad [Q_k, Q_{k'}] = [\Pi_k, \Pi_{k'}] = 0$$

In other words, the normal coordinates and their conjugate momenta obey the same commutation relations as position and momentum operators! Writing the Hamiltonian in terms of these quantities,

$$\mathbf{H} = \sum_k \left(\frac{\Pi_k \Pi_{-k}}{2m} + \frac{1}{2} m\omega_k^2 Q_k Q_{-k} \right)$$

where

$$\omega_k = \sqrt{2\omega^2(1 - \cos(ka))}$$

Notice that the couplings between the position variables have been transformed away; if the *Q*'s and 's were Hermitian (which they are not), the transformed Hamiltonian would describe *N uncoupled* harmonic oscillators. In fact, this Hamiltonian describes a quantum field theory of non-interacting bosons.

It is not *a priori* obvious that these excitations generated by the *a* operators are literally waves of lattice displacement, but one may convince oneself of this by calculating the *position-position correlation function*. Let |*k*> denote a state with a single quantum of mode *k* excited, i.e.

$$|k\rangle = a_k^\dagger |0\rangle$$

One can show that, for any two atoms *j* and *l*,

$$\begin{aligned} \langle k|x_j(t)x_l(0)|k\rangle &= \tfrac{\hbar}{Nm\omega_k} \cos\left[k(j-l)a - \omega_k t\right] \\ &\quad + \langle 0|x_j(t)x_l(0)|0\rangle \end{aligned}$$

This is exactly what we would expect for a lattice wave with frequency *É$_k$* and wave number *k*.

The energy spectrum of this Hamiltonian is easily obtained by the method of ladder operators, similar to the quantum harmonic oscillator problem. We introduce a set of ladder operators defined by

$$\begin{aligned} a_k &= \sqrt{\tfrac{m\omega_k}{2\hbar}}\left(Q_k + \tfrac{i}{m\omega_k}\Pi_{-k}\right) \\ a_k^\dagger &= \sqrt{\tfrac{m\omega_k}{2\hbar}}\left(Q_{-k} - \tfrac{i}{m\omega_k}\Pi_k\right) \end{aligned}$$

The ladder operators satisfy the following identities:

$$\mathbf{H} = \sum_k \hbar\omega_k \left(a_k^\dagger a_k + 1/2\right)$$

$$[a_k, a_{k'}^\dagger] = \delta_{kk'}$$

$$[a_k, a_{k'}] = [a_k^\dagger, a_{k'}^\dagger] = 0.$$

As with the quantum harmonic oscillator, we can then show that $a_k^\dagger$ and a_k respectively create and destroy one excitation of energy É$_k$. These excitations are phonons.

We can immediately deduce two important properties of phonons. Firstly, phonons are bosons, since any number of identical excitations can be created by repeated application of the creation operator $a_k^\dagger$. Secondly, each phonon is a "collective mode" caused by the motion of every atom in the lattice. This may be seen from the fact that the ladder operators contain sums over the position and momentum operators of every atom.

Dispersion relation

The equation obtained above,

$$\omega_k = \sqrt{2\omega^2(1-\cos(ka))}$$

is known as a dispersion relation. It relates the frequency of a phonon, É$_k$, to its wave number k.

The speed of propagation of a phonon, which is also the speed of sound in the lattice, is given by the slope of the dispersion relation, É$_k$/k (see group velocity.) At low values of k (i.e. long wavelengths), the dispersion relation is almost linear, and the speed of sound is approximately Éa, independent of the phonon frequency. As a result, packets of phonons with different (but long) wavelengths can propagate for large distances across the lattice without breaking apart. This is the reason that sound propagates through solids without significant distortion. This behavior fails at large values of k, i.e. short wavelengths, due to the microscopic details of the lattice.

It should be noted that the physics of sound in air is different from the physics of sound in solids, although both are density waves. This is because sound waves in air propagate in a gas of randomly moving molecules rather than a regular crystal lattice.

Three-dimensional phonons

It is straightforward, though tedious, to generalize the above to a three-dimensional lattice. One finds that the wave number k is replaced by a three-dimensional wave vector **k**. Furthermore, each **k** is now associated with *three* normal coordinates. The Hamiltonian has the form

$$\mathbf{H} = \sum_k \sum_{s=1}^{3} \hbar\,\omega_{k,s} \left(a_{k,s}^\dagger a_{k,s} + 1/2\right)$$

The new indices *s = 1, 2, 3* label the polarization of the phonons. In the one dimensional model, the atoms were restricted to moving along the line, so all the phonons corresponded

to longitudinal waves. In three dimensions, vibration is not restricted to the direction of propagation, and can also occur in the perpendicular plane, like transverse waves. This gives rise to the additional normal coordinates, which, as the form of the Hamiltonian indicates, we may view as independent species of phonons.

Crystal momentum

It is tempting to treat a phonon with wave vector **k** as though it has a momentum **k**, by analogy to photons and matter waves. This is not entirely correct, for **k** is not actually a physical momentum; it is called the *crystal momentum* or *pseudomomentum*. This is because **k** is only determined up to multiples of constant vectors, known as reciprocal lattice vectors. For example, in our one-dimensional model, the normal coordinates *Q* and   are defined so that

$$Q_k \equiv Q_{k+K} \quad ; \quad \Pi_k \equiv \Pi_{k+K} \quad \text{where } K = 2n\pi/a$$

for any integer *n*. A phonon with wave number *k* is thus equivalent to an infinite "family" of phonons with wave numbers *k ± 2À/a*, *k ± 4À/a*, and so forth. Physically, the reciprocal lattice vectors act as additional "chunks" of momentum which the lattice can impart to the phonon. Bloch electrons obey a similar set of restrictions.

It is usually convenient to consider phonon wave vectors **k** which have the smallest magnitude (|**k**|) in their "family". The set of all such wave vectors defines the *first Brillouin zone*. Additional Brillouin zones may be defined as copies of the first zone, shifted by some reciprocal lattice vector.

The phonon gas

A crystal lattice at zero temperature lies in its ground state, and contains no phonons. According to thermodynamics, when the lattice is held at a non-zero temperature its energy is not constant, but fluctuates randomly about some mean value. These energy fluctuations are caused by random lattice vibrations, which can be viewed as a *gas of phonons*. (Note: the random motion of the atoms in the lattice is what we usually think of as heat.) Because these phonons are generated by the temperature of the lattice, they are sometimes referred to as **thermal phonons**.

Unlike the atoms which make up an ordinary gas, thermal phonons can be created or destroyed by random energy fluctuations. Their behavior is similar to the *photon* gas produced by an electromagnetic cavity, wherein photons may be emitted or absorbed by the cavity walls. This similarity is not coincidental, for it turns out that the electromagnetic field behaves like a set of harmonic oscillators; see Blackbody radiation. Both gases obey the Bose-Einstein statistics: in thermal equilibrium, the average number of phonons (or photons) in a given state is

$$\langle n_{k,s} \rangle = \frac{1}{\exp(\hbar\omega_{k,s}/k_B T) - 1}$$

where $É_{k,s}$ is the frequency of the phonons (or photons) in the state, k_B is Boltzmann's constant, and *T* is the temperature.

Phonon behavior

Acoustic and optical phonons

In real solids, there are two types of phonons: "acoustic" phonons and "optical" phonons. "Acoustic phonons", which are the phonons described above, have frequencies that become small at the long wavelengths, and correspond to sound waves in the lattice.

"Optical phonons" always have some minimum frequency of vibration, even when their wavelength is large. They are called "optical" because in ionic crystals (like sodium chloride) they are excited very easily by light (in fact, infrared radiation). This is because they correspond to a mode of vibration where positive and negative ions at adjacent lattice sites swing against each other, creating a time-varying electrical dipole moment.

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Roton

Roton is the quantum of rotation in a superfluid. These occur in quantized vortices.

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Subfields of physics

Home | Astrophysics | Atomic, Molecular & Optical Physics | Computational Physics | Condensed Matter Physics | Cosmology | Cryogenics | Fluid Dynamics | Polymer Physics | Optics | Materials Physics | Mechanics | Nuclear Physics | Plasma Physics | Particle Physics | Vehicle Dynamics

Astrophysics

Astrophysics is the part of astronomy that deals principally with the physics of the universe, including luminosity, density, temperature, and the chemical composition of stars, galaxies, and the interstellar medium.

- Theoretical astrophysics

Home | Up | Theoretical Astrophysics

Theoretical astrophysics

Theoretical Astrophysics is the discipline that seeks to explain the phenomena observed by astronomers in physical terms. With this purpose, theoretical astrophysicists create and evaluate models to reproduce and predict the observations. Theoretical astrophysicists use a wide variety of tools which include analytical models (for example, polytropes to approximate the behaviors of a star) and computational numerical simulations. Each has some advantages. Analytical models of a process are generally better for giving you insight into the heart of what is going on. Numerical models can reveal the existence of phenomenon and effects that you would not otherwise see.

Theorists in astrophysics endeavor to create the simplest models possible that are in agreement with observations (from astronomers). Their models/theories must make testable predictions. New data can then be gathered which may be consistent or inconsistent with the theory; in the case of an inconsistency, the model may be discarded or (as is often the case) new complications are added to it.

Topics studied by theoretical astrophysics include: stellar dynamics and evolution; galaxy formation; large-scale structure of matter in the Universe; origin of cosmic rays; and cosmology.

Some widely-accepted theories/models in astrophysics include the Big Bang, Cosmic inflation, dark matter, and fundamental theories of physics. For an example of an astrophysical theory (although one which is not generally accepted by the astrophysical community), see the article Modified Newtonian Dynamics.

See also:

- Astrophysics

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Atomic, molecular, and optical physics

Atomic, molecular, and optical physics is the study of matter-matter and light-matter interactions on the scale of single atoms or structures containing a few atoms. The three areas are grouped together because of their interrelationships, the similarity of methods used, and the commonality of the energy scales that are relevant.

Atomic physics is distinct from nuclear physics, despite their association in the public consciousness. Atomic physics is unconcerned with the nuclear processes studied in nuclear physics, although properties of the nucleus can be important in atomic physics (e.g., hyperfine splitting).

Molecular physics focuses on multi-atomic structures and their internal and external interactions with matter and light.

Optical physics is distinct from optics in that it tends to focus, not on the control of classical light fields by macroscopic objects, but on the fundamental properties of optical fields and their interactions with matter in the microscopic realm.

All three areas include both classical and quantum treatments.

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Computational physics

Computational physics is the study and implementation of numerical algorithms in order to solve problems in physics for which a quantitative theory already exists.

Physicists often have a very precise mathematical theory describing exactly how a system will operate. Unfortunately, it is often the case that solving these equations in order to produce a useful prediction is a computationally difficult problem. This is especially true with quantum mechanics, where only a handful of simple models can be solved exactly. Even apparently simple problems, such as calculating the wavefunction of an electron orbiting an atom in a strong electric field, may require great effort to formulate a practical algorithm.

In addition, quantum mechanical problems are generally exponential in the size of the system (see computational complexity theory).

Many other more general numerical problems fall loosely under the domain of computational physics, although they could easily be considered pure mathematics or part of any number of applied areas. For example:

- Solving differential equations
- Evaluating integrals
- Stochastic methods, specifically the Monte Carlo Method
- Specialised partial differential equation methods, for example the finite difference method and the finite element method
- The matrix eigenvalue problem - i.e. the problem of finding eigenvalues of very large matrices.

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Condensed matter physics

The term *condensed matter* includes the solid and liquid states of matter.
Topics:

- Solid
    - Crystalline solid
        - bandgap
        - Bloch waves (electron waves in lattice)
        - conduction band
        - crystal lattice
        - effective mass
        - electrical conduction
        - electron hole
        - electron gas
        - phonons (lattice vibrations)
        - valence band
    - Amorphous solid
    - Alloy
    - Metal
    - Semiconductor
    - Insulator
    - Luttinger liquid
    - Antiferromagnet
    - Ferromagnet
        - Magnon
        - Magnetic resonance
    - Spin glass
    - Ferroelectric
- Surface
- Interface
- Soft matter
    - Polymer
    - Membrane
    - Liquid crystal
    - Electronic liquid crystal
- Liquid
    - Complex fluid
    - Superfluid
- Granular matter
- Order parameter
- Quasiparticle
- Topological defect

Phenomena

- Superconductivity
- Magnetism
- Hall effect and Quantum Hall effect
- Kondo effect
- Bose-Einstein condensate
- Phase transitions

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Cosmology

Cosmology is the study of the large-scale structure and history of the universe. In particular, it deals with subjects regarding its origin. It is studied by Astronomy, Philosophy, and Religion. See also cosmogony.

Subjects in cosmology include:

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Physical cosmology

- The Friedman-Robertson-Walker metric
- The Big Bang
  - The shape of the universe in big bang theory
- Cosmic Background Radiation
- Beyond the standard Big Bang model
  - Quasi steady state theory
  - Cosmic inflation
- The Ultimate fate of the Universe
- Large Scale Structure of the Cosmos - few 100 Mpc - a few percent of the horizon
- Galaxy Formation and Evolution
- The dark matter problem
- Topological defects
- Cosmic variance
- Dark energy

According to the proposed extreme circumstances during the first minutes of the universe's history, Big Bang cosmologists often co-operate with scientists from areas such as Particle physics.

Alternative cosmologies

- Plasma cosmology
- Steady state theory

Philosophical cosmology

- Presocratic philosophers
- Anthropic principle

Religious cosmology

- Creation myth
- Creationism

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Cryogenics

Cryogenics is the study of low temperatures or the production of the same, and is often confused with cryobiology, the study of the effect of low temperatures on organisms, or the study of cryopreservation. Likewise, cryonics is the nascent study of the cryopreservation of the human body, is not an established science like cryogenics and is generally viewed with skepticism by most scientists and doctors today.

Liquid gases, such as liquid nitrogen and liquid helium, are used in many cryogenic applications. These gases are held in special containers known as Dewar flasks. Dewar flasks are named after their inventor, James Dewar, the man who first liquified hydrogen. Everday vacuum flasks are a Dewar flask fitted in a protective casing.

Leiden,Netherlands is sometimes called "The Coldest Place on Earth", because of the revolutions in cryogenics that happened there. Some of these were the discovery of superconductivity by Heike Kamerlingh Onnes, the liquefaction of helium by Kamerlingh Onnes, and the solidification of helium by Kamerlingh Onnes' pupil, Willem Hendrik Keesom.

The study of superconductivity is called cryoelectronics or cryolectronics. The utilization of these sciences is called cryotronics.

See also:

- superfluidity
- superconductivity

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Polymer physics

Refers to the physics and chemistry of polymer engineering, as well as the reactions involving degradation and polymerisation of polymers and monomers respectively.

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Optics

Optics is a branch of physics that describes the behavior and properties of light and the interaction of light with matter. Optics explains and is illuminated by optical phenomena.

The field of **optics** usually describes the behavior of visible, infrared and ultraviolet light; however since light is an electromagnetic wave, analogous phenomena occur in X-rays, microwaves, radio waves, and other forms of electromagnetic radiation. **Optics** can thus be regarded as a sub-field of electromagnetism. Some optical phenomena depend on the quantum nature of light and as such some areas of optics are also related to quantum mechanics.

Optics, however, as a field is often considered largely separate from the physics community. It has its own identity, societies, and conferences. The pure science aspects of the field are often called Optical Science or Optical Physics. Applied optical sciences are often called optical engineering. Applications of optical enginering related specifically to illumination systems is called illumination engineering. Each of these disciplines tends to be quite different in its applications, technical skills, focus, and professional affiliations.

Because of the wide application of the science of "light" to real-world applications, the area of optical science, and optical engineering tends to be very cross-disiplinary. You will find optical science a part of many related disciplines including electrical engineering, physics, psychology, medicine, and others.

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Classical Optics

Classical or **geometric optics**, sometimes called **ray optics** is the branch of optics that describes light propagation in terms of rays. Rays are bent at the interface between two

dissimilar media, and may be curved in a medium in which the refractive index is a function of position. The ray in geometric optics is perpendicular to the wavefront in physical optics.

- reflection
- refraction
- diffraction
- dispersion
- polarization
- coherence
- scattering
- ray and wave theories of optics
- Fourier optics
- Fermat's principle
- gradient index optics
- optical lens design
- fabrication and testing (optical components)

Geometric optics of:

- lenses
- mirrors
- prisms
- optical instruments

Modern Optics

Modern Optics is a term used to describe areas of optical science and engineering that became popular in the 20th century. These areas of optical science typically relate to the electromagnetic or quantum properties of light but do include other topics.

- quantum optics
- Jones calculus
- lasers
- holography
- crystal optics
- nonlinear optics
- statistical optics
- physical optics
- Fourier optics
- diffractive optics
- guided-wave optics
- integrated optics
- non-imaging optics
- thin-film optics
- optical pattern recognition
- optical processors
- micro-optics
- radiometry

- photometry
- optical modeling and simulation methods

Other Optical Fields

- color science
- illumination engineering
- human visual system
- optical communication systems
- image processing
- pattern recognition
- thermal physics - radiative heat transfer
- optical data storage (science of)
- electronic displays (science of)
- photography (science of)
- information theory
- material science - optical properties
- optical computers

Everyday optics

Optics is part of everyday life. Rainbows and appearances of Fata Morgana or the Green ray are examples of optical phenomena.

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Materials physics

Materials physics is a field of physics concerned with the physical properties of materials. The approach is generally more macroscopic and applied than in condensed matter physics.

See also: Materials science

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Mechanics

Mechanics (Latin *mechanicus*, from the Greek *mechanikos*, "one skilled in machines") is a variety of specialised sciences pertaining to the functions and routine operations of machines, machine-like devices or objects. When preceded by a qualifier, mechanics refers to the study of empirically mechanical functions of a stated quantity or property.

Disciplines of Mechanics

- Acoustic theory
- Biomechanics: study of mechanical properties of biologically created structures.
- Continuum mechanics
- Fluid mechanics
- Lie group symmetries
- Mechatronics
- Newtonian physics = Classical Mechanics
- Quantum MechanicsApply functional analysis to quantum wave functions?
- Statistical mechanics
- Theory of relativity

Home | Up | Acoustic Theory | Continuum Mechanics

Acoustic theory

Classical **acoustic theory** derives from fluid mechanics, and centers on the mathematical description of sound waves. See acoustics for the engineering approach.

In approaching the description of a sound wave the mathematics never give the whole story. The subtleties of thermodynamics are difficult enough to recommend a gradual familiarization with some related problems of vibration such as arise in mechanical sound production: motion of a spring, vibration of a string, equation of motion, harmonic.

Besides the math tools, the preceding examples help inform the beginner's physical intuition with analogies to the periodic compression domains.

The propagation of sound waves in air can be modeled by an equation of motion and an equation of continuity. With some simplifications, they can be given as follows:

$$\rho_0 \frac{\partial}{\partial t}\mathbf{v}(\mathbf{x},t) + \nabla p(\mathbf{x},t) = 0$$

$$\frac{\partial}{\partial t}p(\mathbf{x},t) + \rho_0 c^2 \nabla \cdot \mathbf{v}(\mathbf{x},t) = 0$$

where $p(\mathbf{x},t)$ is the acoustic pressure and $\mathbf{v}(\mathbf{x},t)$ is the acoustic fluid velocity vector, $\mathbf{x}$ is the vector of spatial coordinates *x*,*y*,*z*, *t* is the time, Á$_0$ is the static density of air and *c* is the speed of sound in air.

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Continuum mechanics

Continuum mechanics is a branch of physics that deals with solids and fluids (i.e., liquids and gases). Continuum mechanics makes the assumption that these materials are continuous: the fact that matter is made of atoms is ignored. Therefore, physical quantities, such as space, time, energy, and momentum can be handled in the infinitesimal limit. Differential equations are thus the mathematical tool of choice for continuum mechanics. These differential equations are often derived from fundamental physical laws, such as conservation of mass or conservation of momentum.

The physical laws of solids and fluids should not depend on the coordinate system of the differential equations. Continuum mechanics thus uses tensors, which are mathematical objects that are independent of coordinate system. These tensors can be expressed in coordinate systems, for computational convenience. See tensor analysis for more information.

There are two main branches of continuum mechanics:

- Elasticity, which deals with the physics of solids.
- Fluid Mechanics, which deals with the physics of fluids.

The boundary between these two branches is blurry, because elasticity handles materials with viscosity.

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Nuclear physics

Nuclear physics is that branch of physics concerned with the nucleus of the atom. Topics include:

- Strong interaction
- Radioactivity
- Models of the nucleus
  - liquid drop model
  - shell model
  - interacting boson model
- Fission
- Fusion

Applications

- Nuclear magnetic resonance
- Mössbauer effect
- Nuclear power
- Nuclear weapons

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Plasma physics

Plasma physics is the field of physics which studies the dynamic behaviour of plasmas.

Briefly, it is the study of the statistical properties of a field of charged particles, called a plasma. Sometimes called "the fourth state of matter" (besides solid, liquid, and gas), plasma in this context refers to a gas that has been subjected to enough energy to dissociate atoms from their electrons (ionization), producing a cloud of ions and electrons. Because these particles are ionized (charged), the gas behaves in a different fashion than neutral gas in, for instance, the presence of electromagnetic fields.

A common fluid treatment of plasmas comes from a combination of the Navier Stokes Equations of fluid mechanics and Maxwell's equations of electromagnetism. The resulting set of equations, with appropriate approximations, is called Magnetohydrodynamics (or MHD for short).

Plasma physics is important in astrophysics in that many astronomical objects including stars, accretion disks, nebula, and the interstellar medium consist of plasma.

Fields of active research include (but of course are not limited to):

- Plasma equilibria and stability
- Nuclear fusion
- Plasma diagnostics
- Plasma sources
- Plasma interactions with waves and beams
- Industrial plasmas
- Plasma theory
- Plasma devices
    - Magnetic fusion energy (MFE) -- tokamak, stellarator, reversed field pinch, magnetic mirror
    - Inertial fusion energy (IFE) (also Inertial confinement fusion - ICF)
- Space plasmas, e.g. Earth's magnetosphere
- Plasma cosmology

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Particle physics

Particle physics is a branch of physics that studies the elementary constituents of matter and radiations, and the interactions between them. It is also called **high energy physics**, because many elementary particles do not occur independently in Nature, and can only be detected during energetic collisions of larger particles, as is done in particle accelerators.

Modern particle physics research is focused on subatomic particles, which are smaller than atoms. These include atomic constituents such as electrons, protons, and neutrons (protons and neutrons are actually composite particles, made up of quarks), as well as particles produced by radiative and scattering processes, such as photons, neutrinos, and muons.

Strictly speaking, the term *particle* is something of a misnomer. The objects studied by particle physics obey the principles of quantum mechanics. As such, they exhibit wave-

particle duality, displaying particle-like behavior under certain experimental conditions and wave-like behavior in others. Theoretically, they are described neither as waves nor as particles, but as state vectors in an abstract Hilbert space. For a more detailed explanation, see quantum field theory. Following the convention of particle physicists, we will use "elementary particles" to refer to objects such as electrons and photons, with the understanding that these "particles" display wave-like properties as well.

All the particles observed to date have been catalogued in a quantum field theory called the Standard Model, which is often regarded as particle physics' best achievement to date. The model contains 47 species of elementary particles, some of which can combine to form composite particles, accounting for the hundreds of other species of particles discovered since the 1960s. The Standard Model has been found to agree with almost all the experimental tests conducted to date. However, most particle physicists believe that it is an incomplete description of Nature, and that a more fundamental theory awaits discovery. In recent years, measurements of neutrino mass have provided the first experimental deviations from the Standard Model.

Particle physics has had a large impact on philosophy of science. The reductionist ideas that motivates much of the work in this field has been criticized by various philosophers and scientists. Part of the debate is described below.

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History of particle physics

The idea that matter is composed on elementary particles dates to at least the 6th century BC. The philosophical doctrine of "atomism" was studied by ancient Greek philosophers such as Leucippus, Democritus, and Epicurus. Although Isaac Newton in the 17th century thought that matter was made up of particles, it was John Dalton who formally stated in 1802 that everything is made from tiny atoms.

Dmitri Mendeleev's first periodic table in 1869 helped cement the view, prevalent throughout the 19th century, that matter was made of atoms. Work by J.J. Thomson

established that atoms are composed of light electrons and massive protons. Ernest Rutherford established that the protons are concentrated in a compact nucleus. The nucleus was initially thought to be composed of protons and confined electrons (in order to explain the difference between nuclear charge and mass number), but was later found to be composed of protons and neutrons.

The 20th century explorations of nuclear physics and quantum physics, culminating with proofs of nuclear fission and nuclear fusion, gave rise to an active industry of generating one atom from another, even rendering possible (although not feasible economically) the transmutation of lead into gold. These theories successfully predicted nuclear weapons.

Throughout the 1950s and 1960s, a bewildering variety of particles was found in scattering experiments. This was referred to as the "particle zoo". This term was deprecated after the formulation of the Standard Model during the 1970s in which the large number of particles was explained as combinations of a (relatively) small number of fundamental particles.

The Standard Model of particle physics

The current state of the classification of elementary particles is called the "Standard Model". It describes the strong, weak, and electromagnetic fundamental forces, using mediating bosons known as "gauge bosons". The species of gauge bosons are the photon, W^- and W^+ and Z bosons, and the gluons. The model also contains 24 fundamental particles, which are the constituents of matter. Finally, it predicts the existence of a type of boson known as the Higgs boson, which has yet to be discovered.

Experimental particle physics

In Particle Physics, the major international collaborations are:

- CERN, located on the French-Swiss border near Geneva. Its main facilities are LEP, the Large Electron Positron collider (now dismantled) and the LHC, or Large Hadron Collider (under construction).
- DESY, located in Hamburg, Germany. Its main facility is HERA, which collides electrons or positrons and protons.
- SLAC, located near Palo Alto, USA. Its main facility is PEP-II, which collides electrons and positrons.
- Fermilab, located near Chicago, USA. Its main facility is the Tevatron, which collides protons and antiprotons.
- Brookhaven National Laboratory, located on Long Island, USA. Its main facility is the Relativistic Heavy Ion Collider, which collides heavy ions such as gold ions (it is the first heavy ion collider) and protons.

Many other particle accelerators exist.

Objections against particle physics as reductionism

Within physics itself, there are some objections to the extreme reductionist approach of attempting to explain everything in terms of elementary particles and their interaction. These objections are usually raised by solid state physicists. While the Standard Model itself is not challenged, it is held that testing and perfecting the model is not nearly as important as studying the emerging properties of atoms and molecules, and especially large statistical ensembles of those. These critics claim that even a complete knowledge of the underlying elementary particles will not give complete knowledge of atoms and molecules, knowledge that arguably is more important to us.

Reductionists typically claim that all progress in the sciences has involved reductionism to some extent.

Public policy and particle physics

Experimental results in particle physics are investigated using enormous particle accelerators which typically cost several billion dollars and require large amounts of government funding. Because of this, particle physics research involves issues of public policy.

Many have argued that the potential advances do not justify the money spent, and that in fact particle physics takes money away from more important research and education efforts. In 1993, the US Congress stopped the Superconducting Super Collider because of similar concerns, after $2 billion had already been spent on its construction. Many scientists, both supporters and opponents of the SSC, believe that the decision to stop construction of the SSC was due in part to the end of the Cold War which removed scientific competition with the Soviet Union as a rationale to spend large amounts of money on the SSC.

Some within the scientific community believe that particle physics has also been adversely affected by the aging population. The belief is that the aging population is much more concerned with immediate issues of their health and their parent's health and that this has driven scientific funding away from physics toward the biological and health sciences. In addition, many opponents question the ability of any single country to support the expense of particle physics results and fault the SSC for not seeking greater international funding.

Proponents of particle accelerators hold that the investigation of the most basic theories deserves adequate funding, and that this funding benefits other fields of science in various ways. They point out that all accelerators today are international projects and question the claim that money not spent on accelerators would then necessarily be used for other scientific or educational purposes.

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Vehicle dynamics

Definitions

- Ackermann steering geometry
- Camber angle
- Castor angle
- Circle of forces
- Live axle
- Oversteer
- Understeer
- Unsprung weight

Performance Driving Techniques

- Double declutching
- Handbrake turn
- Heel-and-Toe
- Left-foot braking
- Opposite lock

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Methods

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Scientific method

The scientific method usually refers to either a series or a collection of processes that are considered characteristic of scientific investigation and of the acquisition of new scientific knowledge.

Philosophers, historians and sociologists have found many ways to describe the scientific process. Often when someone describes how they think science is done, they are describing how they think science may be best or most reliably done. As a result, discussions of scientific method are frequently partisan. Indeed, there are perhaps as many methods of doing science as there are methodologists.

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Introduction

The enunciation of a scientific method by Roger Bacon in the thirteenth century described a repeating cycle of observation, hypothesis, experimentation and the need for independent verification. This view, itself inspired by an arab alchemical tradition not endorsed by christian ecclesiastical authority, led to Francis Bacon (in 1620 with the *New Organon*) laying down some methods for identifying causation between phenomena. With these articulations, unfounded speculation and analogical arguments began to be replaced by consistent and logical methods of investigation.

It is common to speak as if a single approach of this type were how scientists operate literally and all the time. Most historians, philosophers and sociologists regard this

perspective as naïve, and view the actual progress of science as more complicated and haphazard. The actual course of scientific progress is inseparable from the politics and culture of science; a single, formal process cannot suffice either to explain or prescribe scientific progress.

The question of how science operates is important well beyond the academic community. In the judicial system and in policy debates, for example, a study's deviation from *accepted scientific practice* is grounds to reject it as "junk science." Whether strictly formularizable or not, science represents a standard of proficiency and reliability, and this is due at least in part to the way scientists work.

The idealized scientific method

The essential elements of the scientific method are traditionally described as follows:

- *Observe:* Observe or read about a phenomenon.
- *Hypothesize:* Wonder about your observations, and invent a hypothesis, a 'guess', which could explain the phenomenon or set of facts that you have observed.
- *Test*
    - *Predict:* Use the logical consequences of your hypothesis to predict observations of new phenomena or results of new measurements.
    - *Experiment:* Perform experiments to test the accuracy of these predictions.
- *Conclude:* Accept or refute hypothesis
    - *Evaluate:* Search for other possible explanations of the result until you can show that your guess was indeed the explanation, with confidence.
    - *Formulate new hypothesis*

These activities do not describe all that scientists do. This simplified method is useful for teaching, since it describes the way in which scientists often think of themselves as acting.

This idealised process is often misinterpreted as applying to scientists individually rather than to the scientific enterprise as a whole. Science is a social activity, and one scientist's theory or proposal cannot become accepted unless it has been published, peer reviewed, criticised, and finally accepted by the scientific community.

Observation

The scientific method begins with observation. Observation often demands careful *measurement*. It also requires the establishment of *operational definitions* of measurements and other relevant concepts. Definitions are not scientific hypotheses; they are not "falsifiable"; they are **always** true or *tautological*. Definitions condense a number of ideas into a single word or phrase. That being said, an observer's definition could differ significantly from commonly understood concepts of a term, and still be correct. Such a definition, however, would carry greater risk of being misunderstood. These definitions are operational in that they may differ with the context of a hypothesis, and they may be refined when the hypothesis is refined.

For example, the term "day" is useful in ordinary life and its meaning may vary with the context. (Do we mean a 24 hour period or do we mean the time between sunrise and sunset?) We don't have to define it precisely to make use of it. In many sciences it is precisely 86,400 atomic seconds. In studying the motion of the Earth, we may use two distinct operational definitions: a *solar day* is the time between two successive observations of the sun at the same position in the sky; a *sidereal day* is the time between two successive observations a specific star sky at the same position. The length of these two kinds of day differs by about four minutes.

Slight differences between operational definitions are often important, as they are needed to make experiments precise enough to distinguish subtle underlying phenomena. An example of this lies in choosing the appropriate segmentation in the statistical analysis of data. Distinctions in operational definitions can also reflect important conceptual differences: for example, *mass* and *weight* are regarded as quite different concepts in science, but the distinction is often ignored in everyday life.

Hypothesis

To explain the observation, scientists use whatever they can (their own creativity (currently not well understood), ideas from other fields, or even systematic guessing, or any other methods available) to come up with possible explanations for the phenomenon under study.

In the twentieth century Karl Popper introduced the idea that a hypothesis must be falsifiable; that is, it must be capable of being demonstrated wrong. Paul Feyerabend argued against this position, providing examples of falsified scientific theories that nevertheless had a vital role in the progress of scientific understanding.

Of course, it is impossible for the scientist to be impartial, considering all known evidence, and not merely evidence which supports the hypothesis under development. But by submitting their theories for peer review, scientists can at least make it more likely that the hypotheses formed will be relevant and useful, or at least get others to agree with it.

In the extremely rare cases where no better grounds for discriminating between rival hypotheses can be found, the bias scientists almost always follow is the principle of Occam's Razor; one chooses the simplest explanation for all the available evidence, in whatever sense "simple" is chosen to be defined (is it that which takes the fewest steps, or combines the smallest number of scientific facts, or takes the fewest words to express, or is the easiest to understand, or is the most predictable, or simply seems the most like common sense, or the average person's idea of common sense, to the scientist(s) judging the model?)

Prediction

A hypothesis must make specific predictions; these predictions can be tested with concrete measurements to support or refute the hypothesis. For instance, Albert Einstein's General Relativity makes a few specific predictions about the structure of space-time, such as the prediction that light bends in a strong gravitational field, and the amount of bending depends in a precise way on the strength of the gravitational field. Observations made during

a 1919 solar eclipse supported the hypothesis (i.e., General Relativity) as against those of the other possible hypotheses which predicted different results. (Later experiments confirmed this even further.)

Deductive reasoning is the way in which predictions are used to test a hypothesis.

Verification

Probably the most important aspect of scientific reasoning is verification: The results of one's experiments must be verified. Verification is the process of determining whether the hypothesis is in accord with empirical evidence, and whether it will continue to be in accord with a more generally expanded body of evidence.

Ideally, the experiments performed should be fully described so that anyone can reproduce them, and many scientists should independently verify every hypothesis. Results which can be obtained from experiments performed by many are termed *reproducible* and are given much greater weight in evaluating hypotheses than non reproducible results.

Scientists must design their experiments carefully. For example, if the measurements are difficult to make, or subject to observer bias, one must be careful to avoid distorting the results by the experimenter's wishes. When experimenting on complex systems, one must be careful to isolate the effect being tested from other possible causes of the intended effect (this results in a *controlled* experiment). In testing a drug, for example, it is important to carefully test that the supposed effect of the drug is produced only by the drug itself, and not by the placebo effect or by random chance. Doctors do this with what is called a double-blind study: two groups of patients are compared, one of which receives the drug and one of which receives a placebo. No patient in either group knows whether or not they are getting the real drug; even the doctors or other personnel who interact with the patients don't know which patient is getting the drug under test and which is getting a fake drug (often sugar pills), so their knowledge can't influence the patients either.

Evaluation

Falsificationism argues that any hypothesis, no matter how respected or time-honoured, *must* be discarded once it is contradicted by new reliable evidence. This is of course an oversimplification, since individual scientists inevitably hold on to their pet theory long after contrary evidence has been found. This is not always a bad thing. Any theory can be made to correspond to the facts, simply by making a few adjustments—called "auxiliary hypothesis"—so as to bring it into correspondence with the accepted observations. The choice of when to reject one theory and accept another is inevitably up to the individual scientist, rather than some methodical law.

Hence *all* scientific knowledge is always in a state of flux, for at any time new evidence could be present that contradicts long-held hypotheses. A classic example is the explanation of light. Isaac Newton's particle paradigm was overturned by the wave theory of light, which explained diffraction, and which was held to be incontrovertible for many decades.The wave paradigm, in turn was refuted by the discovery of the photoelectric effect. The currently held theory of light holds that photons (the 'particles' of light) are both waves and particles;

experiments have been performed which demonstrate that light has both particle and wave properties.

The experiments that reject a hypothesis should be performed by many different scientists to guard against bias, mistake, misunderstanding, and fraud. Scientific journals use a process of *peer review*, in which scientists submit their results to a panel of fellow scientists (who may or may not know the identity of the writer) for evaluation. Scientists are rightly suspicious of results that do not go through this process; for example, the cold fusion experiments of Fleischmann and Pons were never peer reviewed—they were announced directly to the press, before any other scientists had tried to reproduce the results or evaluate their efforts. They have not been reproduced elsewhere as yet; and the press announcement was regarded, by most nuclear physicists, as very likely wrong. Peer review may well have turned up problems and led to a closer examination of the experimental evidence Fleischmann, Pons, et al believed they had. Much embarrassment, and wasted effort worldwide, would have been avoided.

Other aspects of method

There are no definitive guidelines for the production of new hypotheses. The history of science is filled with stories of scientists describing a "flash of inspiration", or a hunch, which then motivated them to look for evidence to support or refute their idea. Michael Polanyi made such creativity the centrepiece of his methodology.

The anecdote that an apple falling on Isaac Newton's head inspired his theory of gravity is a popular example of this (there is no evidence that the apple fell on his head; all Newton said was that his ideas were inspired "by the fall of an apple.") Kekule's account of the inspiration for his hypothesis of the structure of the benzene-ring (dreaming of snakes biting their own tails) is better attested.

Scientists tend to look for theories that are "elegant" or "beautiful"; in contrast to the usual English use of these terms, scientists have a more specific meaning in mind. "Elegance" (or "beauty") refers to the ability of a theory to neatly explain all known facts as simply as possible, or in a manner consistent with Occam's Razor.

The Ptolemaic model of the universe suggested that the earth is the centre of a pristine, perfect universe, and all motions in such a universe must be circular. The model explained the apparent retrograde motion of the planets, by introducing epicycles. Nicolaus Copernicus' model placed the sun at the centre of planetary motion, but also assumed that the planets moved in perfect circles. It also found it necessary to make use of epicycles, and was as complex as, yet less accurate than the heliocentric model. Improvement in the accuracy of the model depended not only on developing the mathematics of elliptical orbits, but a conceptual change in the way in which motion was understood. Tycho Brahe made unprecedentedly accurate observations, but did not reject the geocentric model. It took Kepler 20 years to formulate equations which explained Tycho Brahe's observations in heliocentric terms.

Isaac Newton's System of the World unified Kepler's laws and Galileo's mechanical studies of acceleration, which re-integrated modern science into a comprehensible world model.

Dogged adherence to method can be counterproductive.

History is replete with examples of accurate theories ignored by peers, and inaccurate ones propagated unduly.

Often it is the less accurate theory that eventually becomes accepted.

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Physical quantity

A **physical quantity** is the result of measurement and usually expressed as the product of a numerical value and a physical unit (whereby SI units are usually preferred).

Example:

- $P = 42.3 \times 10^3$ W = 42.3 kW

With

- P being the physical quantity for power;
- 42.3×10^3 being the numerical value which is split up into
    - 42.3 and
    - k, the SI prefix representing 10^3
- W being the symbol for the unit of power, the watt.

Usually, the symbols of physical quantities are chosen to be a single letter of the Latin or Greek alphabet, printed in italic. Both lower and capital letters are used. Often, the symbols are modified by subscripts or superscripts. If these sub- or superscripts are themselves symbols for physical quantities or numbers, they are printed in italic. Other sub- and superscripts are printed upright (roman).

Examples:

- E_p for potential energy (note: p is upright)
- c_p for heat capacity at constant pressure (note: p represents the physical quantity of pressure and is therefore printed italic)

A quantity is called ***extensive*** when its magnitude is additive for subsystems as there are the volume V or the mass m. In cases where the magnitude is independent of the extent of the system (e.g. temperature T, pressure p) the quantity is called ***intensive***. The word ***specific*** is added to an extensive quantity in order to refer to the quantity divided by its mass (e.g. the specific volume $v = V/m$). Similarly, the expression ***molar*** before an extensive quantity means divided by amount of substance (e.g. molar volume $V_\mathrm{m} = V/n$).

See also:

- SI base unit
- length
- mass
- time
- temperature

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Measurement

Measurement is the determination of the size or magnitude of something. Measurement is not limited to physical quantities, but can extend to quantifying almost any imaginable

thing such as degree of uncertainty, consumer confidence, or the rate of increase in the fall in the price of beanie babies.

- "A measurement is a comparison to a standard." -- William Shockley

In physics and engineering, **measurement** is the process of comparing physical quantities of real-world objects and events. Established standard objects and events are used as units, and the measurement results in at least two numbers for the relationship between the item under study and the referenced unit of measurement, where at least one number estimates the statistical uncertainty in the measurement. Measuring instruments are the means by which this translation is made.

Metrology is the study of measurement.

A metric is a standard for measurement. The quantification of phenomena through the process of measurement relies on the existence of an explicit or implicit metric, which is the standard to which the measure is referenced. If I say I am '5', I am indicating a measurement without conveying an applicable standard. I may mean I am 5 years old, 5 feet high, or 5-time world raquetball champion.

Measuring physical quantities accurately is important in science, engineering and commerce.

For example, the unit for length might be a well-known person's foot, and the length of a boat can be given as the number of times that person's foot would fit the length of the boat.

Laws to regulate measurement were originally developed to prevent fraud. However, units of measurement are now generally defined on a scientific basis, and are established by international treaties.

The history of measurements is a topic within the History of Science and Technology. The meter was standardized as the unit for length after the French revolution, and has since been adopted throughout most of the world. The United States and the UK are in the process of converting to the SI system. This process is known as metrication.

Systems of measurement:

- Imperial units
- SI system, also known as the metric system
- Chinese units

Measuring the ratios between physical quantities is an important sub-field of physics.

Some important physical quantities include:

- the speed of light
- the fine-structure constant
- the charge of an electron

See also:

- Dimensional analysis
- conversion of units

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Measuring instrument

In physics and engineering, measurement is the activity of comparing physical quantities of real-world objects and events. Established standard objects and events are used as units,

and the measurement results in a given number for the relationship between the item under study and the referenced unit of measurement. **Measuring instruments** are the means by which this translation is made.

Physicists use a vast range of instruments to perform their measurements. These range from simple objects such as rulers and stopwatches to electron microscopes and particle accelerators.

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Dimensional analysis

Dimensional analysis is a mathematical tool often applied in physics, chemistry, and engineering to simplify a problem by reducing the number of variables to the smallest number of "essential" parameters. Systems which share these parameters are called *similar* and do not have to be studied separately.

The *dimension* of a physical quantity is the type of unit needed to express it. For instance, the dimension of a speed is distance/time and the dimension of a force is mass×distance/time^2. In mechanics, every dimension can be expressed in terms of distance (which physicists often call "length"), time, and mass, or alternatively in terms of force, length and mass. Depending on the problem, it may be advantageous to choose one or the other set of *fundamental units*. Every unit is a product of (possibly fractional) powers of the fundamental units, and the units form a group under multiplication.

In the most primitive form, dimensional analysis is used to check the correctness of algebraic derivations: in every physically meaningful expression, only quantities of the same dimension can be added or subtracted. The two sides of any equation must have the same dimensions. Furthermore, the arguments to exponential, trigonometric and logarithmic functions must be dimensionless numbers, which is often achieved by multiplying a certain physical quantity by a suitable constant of the inverse dimension.

The above mentioned reduction of variables uses the Buckingham À-theorem as its central tool. This theorem describes how every physically meaningful equation involving *n* variables can be equivalently rewritten as an equation of *n*-*m* dimensionless parameters, where *m* is the number of fundamental units used. Furthermore, and most importantly, it provides a method for computing these dimensionless parameters from the given variables, even if the form of the equation is still unknown.

Two systems for which these parameters coincide are called *similar*; they are equivalent for the purposes of the equation, and the experimentalist who wants to determine the form of the equation can choose the most convenient one.

The À-theorem uses linear algebra: the space of all possible physical units can be seen as a vector space over the rational numbers if we represent a unit as the set of exponents needed for the fundamental units (with a power of zero if the particular fundamental unit is not present). Multiplication of physical units is then represented by vector addition within this vector space. The algorithm of the À-theorem is essentially a Gauss-Jordan elimination carried out in this vector space.

A typical application of dimensional analysis occurs in fluid dynamics. If a moving fluid meets an object, it exerts a force on the object, according to a complicated (and not completely understood) law. The variables involved are: the speed, density and viscosity of the fluid, the size of the body, and the force. Using the algorithm of the À-theorem, one can reduce these five variables to two dimensionless parameters: the drag coefficient and the Reynolds number. The original law is then reduced to a law involving only these two numbers. To empirically determine this law, instead of experimenting on huge bodies with fast flowing fluids (such as real-size airplanes in wind-tunnels), one may just as well experiment on small models with slow flowing, more viscous fluids, because these two systems are similar.

Worked example

Consider Einstein's well-known equation $E = mc^2$. As stated above, the two sides of any equation must have the same dimensions. We can check this as follows.

E is energy, which has units of mass × length^2 / time^2. (This is because energy = force × length, and force = mass × acceleration, and acceleration = length / time^2.)

m is mass, which is a unit on its own.

c is speed, which has units of length / time.

The left-hand side, E, therefore has units of mass × length^2 / time^2.

The right-hand side, mc^2, has units of mass × (length / time)^2 = mass × length^2 / time^2.

The two sides therefore have the same dimensions.

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Statistics

Statistics is a branch of applied mathematics which includes the planning, summarizing, and interpreting of uncertain observations. Because the aim of statistics is to produce the "best" information from available data, some authors make statistics a branch of decision theory. As a model of randomness or ignorance, probability theory plays a critical role in the development of statistical theory.

The word *statistics* comes from the modern Latin phrase *statisticum collegium* (lecture about state affairs), from which came the Italian word *statista*, which means "statesman" or "politician" (compare to status) and the German *Statistik*, originally designating the analysis of data about the state. It acquired the meaning of the collection and classification of data generally in the early nineteenth century.

We describe our knowledge (and ignorance) mathematically and attempt to learn more from whatever we can observe. This requires us to

1. plan our observations to control their variability (experiment design),
2. summarize a collection of observations to feature their commonality by suppressing details (descriptive statistics), and
3. reach consensus about what the observations tell us about the world we observe (statistical inference).

In some forms of descriptive statistics, notably data mining, the second and third of these steps become so prominent that the first step (planning) appears to become less important. In these disciplines, data often are collected outside the control of the person doing the analysis, and the result of the analysis may be more an operational model than a consensus report about the world.

The probability of an event is often defined as a number between one and zero rather than a percentage. In reality however there is virtually nothing that has a probability of 1 or 0. You could say that the sun will certainly rise in the morning, but what if an extremely unlikely event destroys the sun? What if there is a nuclear war and the sky is covered in ash and smoke?

We often round the probability of such things up or down because they are so likely or unlikely to occur, that it's easier to recognise them as a probability of one or zero.

However, this can often lead to misunderstandings and dangerous behaviour, because people are unable to distinguish between, e.g., a probability of 10^{-4} and a probability of 10^{-9}, despite the very practical difference between them. If you expect to cross the road about 10^{5} or 10^{6} times in your life, then reducing your risk per road crossing to 10^{-9} will make you safe for your whole life, while a risk per road crossing of 10^{-4} will make it very likely that you will have an accident, despite the intuitive feeling that 0.01% is a very small risk.

Some sciences use applied statistics so extensively that they have specialized terminology. These disciplines include:

- Biostatistics
- Business statistics
- Economic statistics
- Engineering statistics
- Population statistics
- Psychological statistics
- Social statistics (for all the *social* sciences)
- Process analysis and Chemometrics (for analysis of data from analytical chemistry and chemical engineering)

Statistics form a key basis tool in business and manufacturing as well. It is used to understand measurement systems variability, control processes (as in "statistical process control" or SPC), for summarizing data, and to make data-driven decisions. In these roles it is a key tool, and perhaps the only reliable tool.

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List of laws in science

This is a list of physical laws discovered by science.

- Boyle's Law (pressure and volume of ideal gas)
- Charles & Gay-Lussac (gases expand equally with the same change of temperature)
- Dulong-Petit law (specific heat capacity at constant volume)

$$c_V = \frac{3R}{M}$$

- Einstein
  - Relativity $E = mc^2$ (Energy = mass × speed of light^2)
- Laws of Kepler (planetary motion)
- Beer-Lambert (light absorption)
- Newton
  - Newton's laws of motion (inertia, $F = ma$, action and reaction)
  - Law of heat conduction
  - General law of gravitation (universal gravitation force)

$$F_g = \frac{Gm_1m_2}{r_2}$$

- Coulomb's law

$$F = \frac{|q_1q_2|}{4\pi\epsilon_0 r^2}$$

- Ohm's Law

$$V = \frac{I}{R}$$

- Kirchhoff's Laws (current and voltage laws)
- Maxwell's equations (electric and magnetic fields: in vacuum $\nabla\cdot\mathbf{E} = 0$, $\nabla\cdot\mathbf{B} = 0$, $\nabla\times\mathbf{E} = -\mathbf{B}/t$, $\nabla\times\mathbf{B} = c^{-2}\mathbf{E}/t$)
- Poiseuille's law (voluminal laminar stationary flow of incompressible uniform viscous liquid through a cylindrical tube with the constant circular cross-section)

$$\Phi_V = \frac{\pi r^4}{8\eta}\frac{\triangle p^*}{l}$$

- Radiation laws

- ○ Planck's Law of Radiation (spectral density in a radiation of a blackbody)
- ○ Wien's law (wavelength of the peak of the emission of a blackbody) »$_0T$ = k_w
- ○ Stefan-Boltzmann law (total radiation from a blackbody)

$$j^\star = \sigma T^4$$

- Thermodynamics

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Physical constant

In science, a **physical constant** is a physical quantity whose numerical value is fixed. It can be constrasted to a mathematical constant which is a fixed number that does not directly involve a physical measurement.

There are many such constants used in science, some of the most famous of which being: Planck's constant, the gravitational constant and Avogadro's constant (better known as Avogadro's number). Constants can take many forms; some, such as the Planck length represents a fundamental physical distance, others such as the speed of light signifies the maximun speed limit of the universe, yet others are dimensionless quantities such as the fine-structure constant which embodies the interaction between electrons and photons.

Below is a list of physical constants:

Quantity	Symbol	Value	Ref.
speed of light in vacuum	c	299 792 458 m·s^{-1} (defined)	a
permeability of vacuum	¼$_0$	4À × 10^{-7} N A^{-2} (defined)	a
		12.566 370 614... × 10^{-7} N A^{-2}	a
permittivity of vacuum	µ$_0$ = 1/(¼$_0$c^2)	8.854 187 817 ... × 10^{-12} F·m^{-1}	a
characteristic impedance of vacuum	Z_0 = ¼$_0$c	376.730 313 461... © (defined)	a
gravitational constant	G	6.672 59(85) × 10^{-11} m^3·kg^{-1}·s^{-2}	?
Planck's constant	h	6.626 068 76(52) × 10^{-34} J·s	a
Dirac's constant	$\hbar = h$ / (2À)	1.054 571 596(82) × 10^{-34} J·s	a
Planck mass	$m_p = (\hbar c / G)^{1/2}$	2.1767(16) × 10^{-8} kg	a
Planck length	$l_p = (\hbar G / c^3)^{1/2}$	1.6160(12) × 10^{-35} m	a
Planck time	$t_p = (\hbar G / c^5)^{1/2}$	5.3906(40) × 10^{-44} s	a
elementary charge	e	1.602 176 462(63) × 10^{-19} C	a
electron rest mass	m_e	9.109 381 88(72) × 10^{-31} kg	a
proton rest mass	m_p	1.672 621 58(13) × 10^{-27} kg	a
neutron rest mass	m_n	1.674 927 16(13) × 10^{-27} kg	a
atomic mass constant, (unified atomic mass unit)	m_u = 1 u	1.660 538 73(13) × 10^{-27} kg	a
Avogadro's number	L, N_A	6.022 141 99(47) × 10^{23}	a
Boltzmann constant	k	1.380 6503(24) × 10^{-23} J·K^{-1}	a
Faraday constant	F	9.648 534 15(39) × 10^4 C·mol^{-1}	a

gas constant	R	8.314 472(15) J·K^{-1}·mol^{-1}	a
zero of the Celsius scale		273.15 K (defined)	?
molar volume, ideal gas, p = 1 bar, ¸ = 0^0C		22.710 981(40) L·mol^{-1}	a
standard atmosphere	atm	101 325 Pa (defined)	a
fine structure constant	± = ¼$_0$$e^2c$ / (2h)	7.297 352 533(27) × 10^{-3}	a
	±$^{-1}$	137.035 999 76(50)	a
Bohr radius	a_0	5.291 772 083(19) × 10^{-11} m	a
Hartree energy	E_h	4.359 743 81(34) × 10^{-18} J	a
Rydberg constant	R	1.097 373 156 8549(83) × 10^7 m^{-1}	a
Bohr magneton	¼$_B$	9.274 008 99(37) × 10^{-24} J·T^{-1}	a
electron magnetic moment	¼$_e$	-9.284 763 62(37) × 10^{-24} J·T^{-1}	a
Lande g-factor for free electron	g_e	2.002 319 304 386(20)	?
nuclear magneton	¼$_N$	5.050 786 6(17) × 10^{-27} J·T^{-1}	?
proton magnetic moment	¼$_p$	1.410 607 61(47) × 10^{-26} J·T^{-1}	?
proton magnetogyric ratio	$^3{}_p$	2.675 221 28(81) × 10^8 s^{-1}·T^{-1}	?
magnetic moment of protons in H_20, ¼'$_p$	¼'$_p$ / ¼$_B$	1.520 993 129(17) × 10^{-3}	?
proton resonance frequency per field in H_20	^{3}'$_p$ / (2À)	42.576 375 (13) M·Hz·T^{-1}	?
Stefan-Boltzmann constant	Ã	5.670 400(40) × 10^{-8} W·m^{-2}·K^{-4}	a
first radiation constant	c_1	3.741 774 9(22) × 10^{-16} W·m^2	?
second radiation constant	c_2	1.438 769 (12) × 10^{-2} m·K	?
standard acceleration of free fall	g_n	9.80665 m·s^{-2} (defined)	?

Some "constants" are really artifacts of the unit system used, like mks or cgs. In natural units, some of these supposedly physical constants turn out to be mere conversion factors.

References

[a]Peter J. Mohr and Barry N. Taylor, "CODATA Recommended Values of the Fundamental Physical Constants: 1998," *Journal of Physical and Chemical Reference Data,* Vol. 28, No. 6, 1999 and *Reviews of Modern Physics,* Vol. 72, No. 2, 2000.

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SI

The **International System of Units**, abbreviated **SI** (for the French phrase *Système International d'Unités*), is the most widely used system of units. Along with the older cgs (centimetre, gram, second) system, SI is sometimes referred to as the **metric system** (especially in the United States, which has not widely adopted its use in everyday commerce, and the UK where conversion is incomplete).

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Origin

The units of the SI system are decided by international conferences organised by the Bureau International des Poids et Mesures (International Office of Weights and Measures). The SI system was first given its name in 1960, and last added to in 1971.

SI is built on seven SI base units, such as the kilogram and metre. These are used to define various SI derived units. SI also defines a number of SI prefixes to be used with the units: these combine with any unit name to give subdivisions and multiples. For example, the prefix *kilo* denotes a multiple of a thousand, so the *kilo*metre is 1,000 metres, the *kilo*gram 1,000 grams, and so on.

SI writing style

- Symbols are written in lower case except for in symbols where the unit is eponymous, or derived from the name of a person. This means that the symbol for the SI unit for pressure, named for Blaise Pascal, is Pa, whereas the unit itself is written pascal. The official SI brochure lists the symbol for the litre as an allowed exception to the capitalization rules: either capital or lowercase L is acceptable.
- Symbols are written in singular e.g 25 kg (not "25 kgs")
- It is preferable to keep the symbol in upright roman type (for example, kg for kilograms, m for meters), so as to differentiate from (mathematical and physical) variables (for example, *m* for mass, *l* for length).
- A space between the numbers and the symbols: 2.21 kg, $7.3 \cdot 10^2$ m^2
- SI uses spaces to separate decimal digits in sets of three. e.g. 1 000 000 or 342 142 (in contrast to the commas or dots used in other systems e.g. 1,000,000 or 1.000.000).
- SI used only a comma as the separator for decimal fractions until 1997. The number "twenty four and fifty one hundredths" would be written as " 24,51 ". In 1997 the CIPM decided that the British full stop (the "dot on the line", or period) would be the decimal separator in text whose main language is English (" 24.51 "). No allowances were made for alternate decimal separators in other languages; except in English, the comma remains the official standard.

The system can legally be used in every country in the world, and in many countries its use is obligatory. Those countries that still give official recognition to non-SI units (e.g. US, UK) define them in terms of SI units. It was adopted by the 11th General Conference on

Weights and Measures (CGPM) in 1960. (See weights and measures for a history of the development of units of measurement.)

Notes

Americans frequently spell 'metre' as 'meter', and 'litre' as 'liter'; however 'metre' and 'litre' are the official BIPM names for these units, although the American usage has been approved by the US government. The official US spelling for 'deca' is 'deka', though Americans use the international spelling more often than the American one.

The unit 'gram' is also sometimes spelled 'gramme' in English speaking countries, though that is an older spelling. Several other languages use the American spelling. In written practice only the abbreviated (prefixed) symbols are used, avoiding the spelling issue.

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SI base unit

The SI system of units defines seven **SI base units**: fundamental physical units defined by an operational definition.

All other physical units can be derived from these base units: these are known as SI derived units. Derivation is by dimensional analysis. Use SI prefixes to abbreviate long numbers.

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Length (*l*)

Unit: metre (m)

One metre is defined as the distance light travels in a vacuum in 1/299792458 second. This standard was adopted in 1983, when the speed of light in vacuum was defined to be precisely 299792458 m/s.

Mass (*m*)

Unit: kilogram (kg)

One kilogram is defined to be the mass of a specific cylinder of platinum-iridium alloy, kept at the International Bureau of Weights and Measures (near Paris). There is an ongoing effort to introduce a definition by way of fundamental or atomic constants.

Time (*t*)

Unit: second (s)

One second is defined as the time required for 9192631770 cycles of the transition between the two hyperfine levels of the ground state of caesium 133. This definition was adopted in 1967.

Electric current (*I*)

Unit: ampere (A)

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

Thermodynamic temperature (*T*)

Unit: Kelvin (K)

The Kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. Named after Lord Kelvin.

Amount of substance (*n*)

Unit: mole (mol)

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol".
2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

Luminous Intensity (*I*)

Unit: candela (cd)

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

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SI derived unit

SI derived units are part of the SI system of measurement units and are derived from the seven SI base units.

Physical quantity	Name of SI unit	Symbol for SI unit	Expression in terms of SI base units	
		Special names and Symbols		
frequency	hertz	Hz	s^{-1}	
force	newton	N	$kg \cdot m \cdot s^{-2}$	
pressure, stress	pascal	Pa	$N \cdot m^{-2}$	$= kg \cdot m^{-1} \cdot s^{-2}$
energy, work, heat	joule	J	$N \cdot m$	$= kg \cdot m^2 \cdot s^{-2}$
power, radiant flux	watt	W	$J \cdot s^{-1}$	$= kg \cdot m^2 \cdot s^{-3}$
electric charge	coulomb	C	$A \cdot s$	
electric potential, electromotive force	volt	V	$J \cdot C^{-1}$	$= m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
electrical resistance	ohm	©	$V \cdot A^{-1}$	$= m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	$A \cdot V^{-1}$	$= s^3 \cdot A^2 \cdot m^{-2} \cdot kg^{-1}$
electric capacitance	farad	F	CV^{-1}	$= s^4 \cdot A^2 \cdot m^{-2} \cdot kg^{-1}$
magnetic flux density, magnetic inductivity	tesla	T	$V \cdot s \cdot m^{-2}$	$= kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux	weber	Wb	$V \cdot s$	$= m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
inductance	henry	H	$Vs \cdot A^{-1}$	$= m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
temperature	degree Celsius	°C	K	
plane angle	radian	rad	1	$= m \cdot m^{-1}$
solid angle	steradian	sr	1	$= m^2 \cdot m^{-2}$
luminous flux	lumen	lm	$cd \cdot sr$	
illuminance	lux	lx	$cd \cdot sr \cdot m^{-2}$	
activity (radioactive)	becquerel	Bq	s^{-1}	
absorbed dose (of radiation)	gray	Gy	$J \cdot kg^{-1}$	$= m^2 \cdot s^{-2}$
dose equivalent (dose equivalent index)	sievert	Sv	$J \cdot kg^{-1}$	$= m^2 \cdot s^{-2}$
catalytic activity	katal	kat	$mol \cdot s^{-1}$	
		Other Quantities		
area			m^2	

volume	m^3	
speed, velocity	$m\cdot s^{-1}$	
angular velocity	s^{-1}, $rad\cdot s^{-1}$	
acceleration	$m\cdot s^{-2}$	
moment of force	$N\cdot m$	$= m^2\cdot kg\cdot s^{-2}$
wavenumber	m^{-1}	
density, mass density	$kg\cdot m^{-3}$	
specific volume	$m^3\cdot kg^{-1}$	
amount (-of-substance) concentration	$mol\cdot m^{-3}$	
molar volume	$m^3\cdot mol^{-1}$	
heat capacity, entropy	$J\cdot K^{-1}$	$= m^2\cdot kg\cdot s^{-2}\cdot K^{-1}$
molar heat capacity, molar entropy	$J\cdot K^{-1}\cdot mol^{-1}$	$= m^2\cdot kg\cdot s^{-2}\cdot K^{-1}\cdot mol^{-1}$
specific heat capacity, specific entropy	$J\cdot K^{-1}\cdot kg^{-1}$	$= m^2\cdot s^{-2}\cdot K^{-1}$
molar energy	$J\cdot mol^{-1}$	$= m^2\cdot kg\cdot s^{-2}\cdot mol^{-1}$
specific energy	$J\cdot kg^{-1}$	$= m^2\cdot s^{-2}$
energy density	$J\cdot m^{-3}$	$= m^{-1}\cdot kg\cdot s^{-2}$
surface tension	$N\cdot m^{-1}=J\cdot m^{-2}$	$= kg\cdot s^{-2}$
heat flux density, irradiance	$W\cdot m^{-2}$	$= kg\cdot s^{-3}$
thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$	$= m\cdot kg\cdot s^{-3}\cdot K^{-1}$
kinematic viscosity, diffusion coefficient	$m^2\cdot s^{-1}$	
dynamic viscosity	$N\cdot s\cdot m^{-2} = Pa\cdot s$	$= m^{-1}\cdot kg\cdot s^{-1}$
electric charge density	$C\cdot m^{-3}$	$m^{-3}\cdot s\cdot A$
electric current density	$A\cdot m^{-2}$	
conductivity	$S\cdot m^{-1}$	$= m^{-3}\cdot kg^{-1}\cdot s^3\cdot A^2$
molar conductivity	$S\cdot m^2\cdot mol^{-1}$	$= kg^{-1}\cdot mol^{-1}\cdot s^3\cdot A^2$
permittivity	$F\cdot m^{-1}$	$= m^{-3}\cdot kg^{-1}\cdot s^4\cdot A^2$;
permeability	$H\cdot m^{-1}$	$= m\cdot kg\cdot s^{-2}\cdot A^{-2}$
electric field strength	$V\cdot m^{-1}$	$= m\cdot kg\cdot s^{-3}\cdot A^{-1}$
magnetic field strength	$A\cdot m^{-1}$	
luminance	$cd\cdot m^{-2}$	
exposure (X and gamma rays)	$C\cdot kg^{-1}$	$= kg^{-1}\cdot s\cdot A$
absorbed dose rate	$Gy\cdot s^{-1}$	$= m^2\cdot s^{-3}$

References:

- I. Mills, Tomislav Cvitas, Klaus Homann, Nikola Kallay, IUPAC: *Quantities, Units and Symbols in Physical Chemistry*, 2nd edition (June 1993), Blackwell Science Inc (p. 72)

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SI prefix

An **SI prefix** is a prefix which can be applied to any unit of the **International System of Units** (SI) to give subdivisions and multiples of that unit.

For example, the prefix "kilo" multiplies by one thousand, so a *kilo*metre is 1,000 metres, and a *kilo*watt is 1,000 watts. The prefix "milli" subdivides by a thousand, so a *milli*metre is one thousandth of a metre (1,000 millimetres in a metre), and a *milli*litre is one thousandth of a litre. The ability to apply the same prefixes to any SI unit is one of the key strengths of the SI, since it considerably simplifies the system's learning and use.

The most commonly used prefixes include:

giga = 10^9, US billion or European milliard, a thousand million

mega = million

kilo = thousand

centi = one hundredth

milli = one thousandth

The full table follows below.

(Sub)multiple	Prefix	Symbol	Name (Americas)	Name (European)
10^{24}	yotta	Y	Septillion	Quadrillion
10^{21}	zetta	Z	Sextillion	Thousand trillion (Trilliard)
10^{18}	exa	E	Quintillion	Trillion
10^{15}	peta	P	Quadrillion	Thousand billion (Billiard)
10^{12}	tera	T	Trillion	Billion
10^{9}	giga	G	Billion	Thousand million (Milliard)
10^{6}	mega	M	Million	
10^{3}	kilo	k	Thousand	
10^{2}	hecto	h	Hundred	
10^{1}	deca or deka	da	Ten	
10^{-1}	deci	d	Tenth	
10^{-2}	centi	c	Hundredth	
10^{-3}	milli	m	Thousandth	
10^{-6}	micro	¼	Millionth	
10^{-9}	nano	n	Billionth	Milliardth
10^{-12}	pico	p	Trillionth	Billionth
10^{-15}	femto	f	Quadrillionth	Billiardth
10^{-18}	atto	a	Quintillionth	Trillionth
10^{-21}	zepto	z	Sextillionth	Trilliardth
10^{-24}	yocto	y	Septillionth	Quadrillionth

Examples:

- 5 cm = 5×10^{-2} m = 5 × 0.01 m = 0.05 m
- 3 MW = 3×10^{6} W = 3 × 1 000 000 W = 3 000 000 W

The prefix always takes precedence over any exponentiation; thus *km*^{2} means *square kilometre* and not *kilo - square metre*. For example, 3 km^2 is equal to 3,000,000 m^2 and *not* to 3,000 m^2 (*nor* to 9,000,000 m^2).

Prefixes where the exponent is divisible by three are recommended. Hence '100 metres' rather than 'one hectometre'. Notable exceptions include centimetre, hectare (hecto-are), centilitre, and 1 dm^3 (equivalent to one litre).

The accepted pronunciation of the initial G of "giga-" was once soft, /Èd’ajgY/ (like "gigantic"), but now the hard pronunciation, /ÈgjgY/, is probably more common.

Note that the formal SI metric prefix for 1000 is lower case "k".

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Use outside SI

The abbreviation "k" is often used to mean a multiple of a thousand, so one may talk of "a 40K salary" (40,000), or the Y2K problem.

Non-SI units

SI prefixes rarely appear coupled with imperial units except in some specialised cases (*e.g.* megaton). They are often used with cgs units in situations where these are still found (*e.g.* millitorr). They are also used with "natural" units in some fields (*e.g.* megaelectron volt, gigaparsec).

Computing

k and greater are common in computing, where they are applied to information and storage units like the bit and the byte. Since these often naturally come in powers of two, the prefixes' meaning changes:

K = 2^{10} = 1,024
M = 2^{20} = 1,048,576
G = 2^{30} = 1,073,741,824
T = 2^{40} = 1,099,511,627,776
P = 2^{50} = 1,125,899,906,842,624.

However, these prefixes usually retain their powers-of-1000 meanings when used to describe rates of data communication (bit rates): 10 Mb/s Ethernet runs at 10,000,000 b/s, not 10,485,760 b/s.

This inconsistency did not seem relevant when computers had little storage and communication links were relatively slow, but the increasing capacity of computing systems and speed of network links began making this inconsistency a more serious problem.

Accordingly, the International Electrotechnical Commission adopted new binary prefixes in 1998, formed from the first syllable of the decimal prefix plus 'bi' (pronounced 'bee'). The symbol is the decimal symbol plus 'i'. So now, one kilobyte (1 kB) equals 1000 bytes, whereas one kibibyte (1 KiB) equals 2^{10} = 1024 bytes. Likewise mebi (2^{20}), gibi (2^{30}), tebi (2^{40}), pebi (2^{50}), and exbi (2^{60}). For example, at 1 MB/s = 10^6 bytes per second, it would take slightly longer than one second to transfer an object 1 MiB = 2^{20} bytes in size. The adoption of these prefixes has been very limited.

† Britain, Ireland and Australia previously used the European number name conventions, but have now largely switched to US usage. Note in particular that above a million and below a millionth, the *same* name has different values in the two naming systems, so *billion* and *trillion* (for example) become unfortunately potentially ambiguous terms internationally. Using the SI prefixes can circumvent this problem. See number names for the details.

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Conversion of units

This article lists **conversion factors** between a number of units.

Name of unit	Symbol	Relation to SI units
	Length, l	
meter (SI base unit)	m	
micron	¼	= ¼m = 10^{-6} m
ångström	Å	= 10^{-10} m
bohr (au)	a_0, b	~ 5.291 77 × 10^{-11} m
x unit	X	~ 1.002 × 10^{-13} m
Fermi		= 1×10^{-15} m
inch	in	= 2.54 × 10^{-2} m
foot	ft	= 12 in = 0.3048 m
yard	yd	= 3 ft = 0.9144 m
mile	mi	= 1760 yd = 1609.344 m
nautical mile		= 1852 m ~ 6076.1 feet
geographical mile		= 1855 m = 6087.15 feet
astronomical unit	AU	= 1.495 978 706 6 × 10^{11} m
parsec	pc	= 3.085 677 580 666 31 × 10^{16} m
light year	l.y.	= 9.460 730 473 × 10^{15} m
light second		= 2.997 924 58 × 10^8 m
mil		= 1×10^{-3} in = 2.54 ×$10^{-5\text{ m}}$ m
Rod		= 5.029 210 058 42 m
Chain		= 20.116 840 233 7 m
Fathom		= 1.8288 m
	Area, A	

square metre (SI unit)	m^2	
barn	b	10^{-28} m^2
acre		~ 4046.856 m^2
are	a	= 100 m^2
hectare	ha	= 10^4 m^2
	Volume, V	
cubic metre (SI unit)	m^3	
litre	l, L	= dm^3 = 10^{-3} m^3
lambda	»	= ¼l = 10^{-6} dm^3
barrel (US)		~ 158.987 dm^3
gallon (US)	gal (US)	E 3.785 41 dm^3
gallon (UK)	gal (UK)	= 4.546 09 dm^3
fluid ounce (US)	fl. oz. (US)	E 29.57 ml
fluid ounce (Imperial)	fl. oz. (Imp.)	E 28.41 ml
	Mass, m	
kilogram (SI base unit)	kg	
electron mass (au)	m_e	~ 9.109 39 × 10^{-31} kg
unified atomic mass unit, dalton	u, Da	~ 1.660 540 × 10^{-27} kg
gamma	³	= ¼g
tonne	t	= 10^3 kg
pound (avoirdupois)	lb, in physics "lbm"	= 0.453 592 37 kg
ounce (avoirdupois)	oz	~ 28.349 5 g
ounce (troy)	oz (troy)	~ 31.103 5 g
grain	gr	= 64.798 91 mg
	Time, t	
second (SI base unit)	s	
au of time		~ 2.418 88 × 10^{-17} s
minute	min	= 60 s
hour	h	= 3600 s
day	d	= 86 400 s (not exactly defined due to leap seconds)
year	a	~ 31 556 952 s
svedberg	Sv	~ 10^{-13} s
	Acceleration, a	
(SI unit)	$m \cdot s^{-2}$	
standard acceleration of free fall	g_n	= 9.806 65 $m \cdot s^{-2}$
galileo	Gal	= 10^{-2} $m \cdot s^{-2}$
	Force, F	
newton (SI unit)	N	= $kg \cdot m \cdot s^{-2}$
dyne (cgs unit)	dyn	= 10^{-5}N
au of force		~ 8.238 73 × 10^{-8}N
pound-force	lbf	E 4.448 22 N
kilogram-force	kgf	= 9.806 65 N
	Pressure, p	

pascal (SI unit)	Pa	= N·m^{-2} = kg·m^{-1}·s^{-2}
atmosphere	atm	= 101 325 Pa
bar	bar	= 10^5 Pa
torr	Torr	= (101 325/760) Pa ~ 133.322 Pa
millimetre of mercury (conventional)	mmHg	= 13.5951 × 980.655 × 10^{-2} Pa ~ 133.322 Pa (= 1 torr)
millimetre of water (4°C)	mm H2O	= 9.806 38 Pa
pounds per square inch	psi	~ 6.894 757 × 10^3 Pa
Electric current, I		
ampere (SI base unit)	A	
esu per second (cgs unit)	esu.s^{-1}	~ ?? A
electromagnetic unit (cgs unit)	abamp	~ ?? A
Electric charge, Q		
coulomb (SI unit)	C	= A.s
statcoulomb, electrostatic unit (cgs unit)	statC, esu	~ 3.335 6 × 10^{-10} C
Voltage, Electromotive force, U		
volt (SI unit)	V	= N·m·C^{-1}
statvolt (cgs unit)	statV	=299.792458 V
Electrical resistance, R		
ohm (SI unit)	ohm	= V·A^{-1}
Energy, U		
joule (SI unit)	J = N·m	= kg·m^2·s^{-2}
erg (cgs unit)	erg	= 10^{-7} J
hartee (au)	E_h	~ 4.359 75 × 10^{-18} J
rydberg	Ry	~ 2.179 87 × 10^{-18} J
electronvolt	eV	= e × V ~ 1.602 18 × 10^{-19} J
calorie, thermochemical	cal_{th}	= 4.184 J
calorie, international	cal_{IT}	= 4.1868 J
15 °C calorie	cal_{IT}	~ 4.1855 J
litre atmosphere	l atm	= 101.325 J
British thermal unit	Btu	E 1055.06 J
Board of Trade Unit or kilowatt-hour	B.O.T.U. or kW·h	= 3.6 × 10^6 J
Power, P		
watt (SI unit)	W	= J·s^{-1} = N·m·s^{-1} = kg·m^2·s^{-3}
horsepower	hp	E 745.7 W
Action, Angular momentum, L, J		
SI unit	J·s = N·m·s	= kg·m^2·s^{-1}
cgs unit	erg·s	= 10^{-7} J·s
au of action	$\hbar$	= h/2À E 1.054 57 × 10^{-34} J·s
Dynamic viscosity, ·		
SI unit	Pa·s = N·m^{-2}·s	= kg·m^{-1}·s^{-1}
poise	P	= 10^{-1}Pa·s
centipoise	cP	= mPa·s
Kinematic viscosity, ½		

SI unit	$m^2 \cdot s^{-1}$	
stokes	St	$= 10^{-4} m^2 \cdot s^{-1}$
Temperature, *T*		
kelvin (SI base unit)	K	
degree Celsius	°C	T[°C] = T[K] - 273.15
degree Fahrenheit	°F	T [°F] = 1.8 (T [°C]) + 32
degree Rankine	°R	= (5/9) K

Note that lbm is pound mass, not pound meter!

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Physical unit

In physics and metrology, units are standards for measurement of physical quantities that need clear definitions to be useful. Reproducibility of experimental results is central to the scientific method. To facilitate this we need standards, and to get convenient measures of the standards we need a **system of units**. Scientific systems of units are a formalization of the concept of weights and measures, initially developed for commercial purposes.

Different systems of units are based on different choices of a set of fundamental units. The most widely used system of units is the international system, or SI system, of units derived from the seven SI base units. All other SI units can be derived from these base units.

Other systems of units that have been used for various purposes include:

- the centimeter-gram-second system of units
- the Planck units
- U.S. customary units
- Imperial units
- Chinese unit

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Units as dimensions

Any value of a physical quantity is expressed as a comparison to a unit of that quantity. For example, the value of a physical quantity Q is written as the product of a unit [Q] and a numerical factor:

$$Q = n * [Q] = n [Q]$$

The multiplication sign is usually left out, just as it is left out between variables in scientific notation of formulas. In formulas the unit [Q] can be treated as if it was a kind of physical dimension: see dimensional analysis for more on this treatment.

A distinction should be made between units and standards. A unit is fixed by its definition, and is independent of physical conditions such as temperature. By contrast, a standard is a physical realization of a unit, and realizes that unit only under certain physical conditions. For example, the metre is a unit, while a metal bar is a standard. One metre is the same length regardless of temperature, but a metal bar will be one metre long only at a certain temperature.

Basic and derived units

For most quantities a unit is absolutely necessary to communicate values of that physical quantity. Try for example to tell someone the value of a length without the use of a unit. That is not possible because you can't verbally describe a length.

But not all quantities require a unit of their own. Using physical laws, units of quantities can be expressed as combinations of units of other quantities. Thus only a small set of units is required. These units are taken as the *basic units*. Other units are *derived units*. Derived units are a matter of convenience, as they can be expressed in terms of basic units. Which units are considered *basic* is a matter of choice.

The basic units of SI are actually not the smallest set. Smaller sets have been defined. There are sets in which the electric and magnetic field have the same unit. This is based on physical laws that show that electric and magnetic field are actually different manifestations of the same phenomenon. In some fields of science such systems of units are highly favored over the SI system.

Conversion of units

Conversion of units involves comparison of different standard physical values, either of a single physical quantity or of a physical quantity and a combination of other physical quantities.

Thus conversion factors between units are always imprecise to some level and improved values may be found when a more precise comparison is performed.

Prefixes in the SI system

In the SI system some letters denoting conveniently chosen numerical values can be used as prefixes to any of the units.

For example, c = 0.01, and thus cm = 0.01 * m and cN = 0.01 * N

There is one exception: for historical reasons, the unit of mass, kg, already contains a prefix and prefixes are not to be added to it but to g. Thus: mg and not μkg (with "μ" = "micro-"). To many this is a source of mistakes and frustration.

Use of prefixes does not involve any unit conversion, as the prefixes are just *defined* as numerical values. They can not be imprecise.

For example, the expressions 'cm' and '0.01 m' mean mathematically exactly the same thing. It is not a unit conversion, just a mathematical conversion, just like '4 * 5' and '20' are mathematical expressions with the same meaning.

Calculations with units

Hints:

- Use formulas involving physical values whenever possible, be reluctant to split up physical values into units and numerical values, as you increase the complexity by a factor of two!
- If you calculate the value of a physical quantity A from a formula involving a combination of other physical quantities (B, C, D), you don't have to calculate the resulting unit: if you just convert all values of B, C, D so as to be expressed in SI units (no prefixes), the resulting unit is the SI unit of the quantity A. The SI system is set up to ensure this convenience. Don't use the gram instead of the kilogram, because naturally that will not work!
- Don't let definitions like *density is mass per unit volume* obscure your understanding of units. It sounds as if it says:

D = m / [V] (WRONG)

This is not true. The correct statement is that density is mass divided by volume:

D = m / V

The sentence `density is mass per unit volume' uses another way of perceiving the concept. It says that the density D_s of system s is the mass m_u of a subsystem u of s, divided by the volume V_u of subsystem u, given that the volume of subsystem u is unit volume:

D_s = m_u / V_u

V_u = 1 [V]

Mathematical rules for calculations with units follow from the formula for physical values, Q = n * [Q]

- Values of the same quantity can of course always be added, but not by just adding their numerical values. The numerical value is not all of the value of the physical quantity.

The units in the physical values have to be *converted* so that they are the same. Then the numerical values can be added. The same principle is known from adding fractions: you have to make the denominators the same and then you can add the numerators.

- When a unit is divided by itself, the division yields a unitless 1.
- When two different units are multiplied by each other, the result is a new unit. For instance, in SI, the unit of momentum is one kilogram multiplied by one meter divided by one second. See also dimensional analysis.
- Expressing a physical value in terms of another unit:

Starting with:

Q = n_i * [Q]_i

just replace the origional unit [Q]_i with its meaning in terms of the desired unit [Q]_f, *e.g.* if [Q]_i = c_ij * [Q]_f, then:

Q = n_i * c_ij * [Q]_f

Now n_i and c_ij are both numerical values, so just calculate their product.

Or, which is just mathematically the same thing, multiply Q by unity, the product is still Q:

Q = n_i * [Q]_i * (c_ij * [Q]_f/[Q]_i)

For example, you have an expression for a physical value Q involving the unit *feet per second* ([Q]_i) and you want it in terms of the unit *miles per hour* ([Q]_f):

1. Find facts relating the original unit to the desired unit:
   1 mile = 5280 feet and 1 hour = 3600 seconds

2. Next use the above equations to construct a fraction that has a value of unity and that contains units such that, when it is multiplied with the original physical value, will cancel the original units:
   1 = (1 mile) / (5280 feet) and 1 = (3600 seconds) / (1 hour)

3. Last, multiply the original expression of the physical value by the fraction, called a *conversion factor*, to obtain the same physical value expressed in terms of a different unit. Note: since the conversion factors have a numerical value of unity, multiplying any physical value by them will not change that value.

See also: units unit conversion computer program

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History of physics

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History of Physics

This article has changed substantially from its original form as the "Ridiculously Brief History of Physics" on the main Physics page. However, further work is needed to fill in some obvious gaps, and to include more detail about the development of physics (and, concurrently, astromomy and mathematics) in non-European cultures. It is intended that this article should grow to be a brief but comprehensive history of physics. The history on the Physics page should remain as a summary only.

This article is a work in progress: please add more material here

Antiquity

Since antiquity, people have tried to understand the behavior of matter: why unsupported objects drop to the ground, why different materials have different properties, and so forth. Also a mystery was the character of the universe, such as the form of the Earth and the behavior of celestial objects such as the Sun and the Moon. Several theories were proposed, most of them were wrong, but this is part of the nature of the scientific enterprise, and even modern theories of quantum mechanics and relativity are considered merely as

"theories that haven't broken yet". Physical theories in antiquity were largely couched in philosophical terms, and rarely verified by systematic experimental testing.

Typically the behaviour and nature of the world were explained by invoking the actions of gods. Around 200 BC, many Greek philosophers began to propose that the world could be understood as the result of natural processes. Many also challenged traditional ideas presented in mythology, such as the origin of the human species (anticipating the ideas of Charles Darwin), although this falls into the history of biology, not physics.

Due to the absence of advanced experimental equipment such as telescopes and accurate time-keeping devices, experimental testing of many such ideas was impossible or impractical. There were exceptions and there are anachronisms: for example, the Greek thinker Archimedes derived many correct quantitative descriptions of mechanics and also hydrostatics when, so the story goes, he noticed that his own body displaced a volume of water while he was getting into a bath one day. Another remarkable example was that of Eratosthenes, who deduced that the Earth was a sphere, and accurately calculated its circumference using the shadows of vertical sticks to measure the angle between two widely separated points on the Earth's surface. Greek mathematicians also proposed calculating the volume of objects like spheres and cones by dividing them into very thin disks and adding up the volume of each disk - anticipating the invention of integral calculus by almost two millennia.

Modern knowledge of these early ideas in physics, and the extent to which they were experimentally tested, is sketchy. Almost all direct record of these ideas was lost when the Library of Alexandria was destroyed, around 400 AD. Perhaps the most remarkable idea we know of from this era was the deduction by Aristarchus of Samos that the Earth was a planet that travelled around the Sun once a year, and rotated on its axis once a day (accounting for the seasons and the cycle of day and night), and that the stars were other, very distant suns which also had their own accompanying planets (and possibly, lifeforms upon those planets).

The discovery of the Antikythera mechanism points to a detailed understanding of movements of these astronomical objects, as well as a use of gear-trains that pre-dates any other known civilization's use of gears.

Regrettably, this period of inquiry into the nature of the world was eventually stifled by a tendency to accept the ideas of eminent philosophers, rather than to question and test those ideas. New discoveries, such as Pythagoras's deduction of the existence of irrational numbers, were suppressed, and technical knowledge was turned increasingly to the development of advanced weapons, rather than experimental investigations of nature. For one thousand years following the destruction of the Library of Alexandria, Ptolemy's (not to be confused with the Egyptian Ptolemies) model of an Earth-centred universe with planets moving in perfect circular orbits was accepted as absolute truth.

We should mention physics and astronomy outside Europe at this stage, especially Mesoamerican, Babylonian, Arabic and Chinese astronomy. The Japanese were also very big on mathematical puzzles - it's not exactly physics but it might be a worthwhile aside, to make this history more balanced. We also need to include a lot about middle-eastern physics, here's a start...(The section Middle Ages)

The Middle Ages & Islamic contibutions to the Sciences

When the power of Greek civilization was eclipsed by the Roman Empire, many Greek doctors began to practice medicine for the Roman elite, but sadly the physical sciences were not so well supported. Following the collapse of the Roman Empire, Europe entered the so-called Dark Ages, and almost all scientific research ground to a halt. The rise of Christianity saw the suppression and destruction of most classical Greek philosophy (along with Greek and Roman art, literature and religious iconography) as heretical and pagan. In the Middle East, however, many Greek natural philosophers were able to find support in the newly created Arab Caliphate (Empire), and the Islamic scholars built upon previous work in medicine, astronomy and mathematics while developing such new fields as alchemy (chemistry). For example, the scholar Muhammad ibn Musa al-Khwarizmi gave his name to what we now call an algorithm, and the word algebra is derived from *al-jabr*, the beginning of the name of one of his publications in which he developed a system of solving quadratic equations, thus beginning Al-gebra.

It is sometime assumed that the Islamic civilization simply preserved the older learning without any innovation. In astronomy, chemistry, and mathematics, at least, this is certainly not true.

Could someone write about what Arabs, Persians and others actually did in **physics***?* Arab Alchemy inspired both Roger Bacon and Isaac Newton.

The monk Roger Bacon conducted experiments into optics, although much of it was similar to what had been done and was being done at the time by Arab scholars. He did make a major contribution to the development of science in medieval Europe by writing to the Pope to encourage the study of natural science in university courses and compiling several volumes recording the state of scientific knowledge in many fields at the time. He described the possible construction of a telescope, but there is no strong evidence of his having made one. He recorded the manner in which he conducted his experiments in precise detail so that others could reproduce and independently test his results - a cornerstone of the scientific method. *The relation of this to earlier Islamic experimental work ought to be explored here.*

The withdrawal of the Islamic empire from Mediterranean Europe (especially Spain) in the 15th century coincided with the dawn of the Renaissance. This "rebirth" of European culture was in part brought about by the re-discovery of those elements of ancient Greek, Indian, Chinese and Islamic culture preserved and further developed by Islam from the 8th to the 15th centuries, and translated by Christian Monks into Latin.

16th century

In the 16th century Nicholas Copernicus revived the heliocentric model of the solar system devised by Aristarchus (which survives primarily in a passing mention in the Sand Reckoner of Archimedes). When this model was published at the end of his life, it was with a preface by Osiander that piously represented it as only a mathematical convenience for calculating the positions of planets, and not an account of the true nature of the planetary orbits.

In England William Gilbert (1544-1603) studied magnetism and published a seminal work, *De Magnete* (1600), in which he thoroughly presented his numerous experimental results.

17th century

In the early 17th century Kepler formulated a model of the solar system based upon the five Platonic solids, in an attempt to explain why the orbits of the planets had the relative sizes they did. His access to extremely accurate astronomical observations by Tycho Brahe enabled him to determine that his model was inconsistent with the observed orbits. After a heroic seven-year effort to more accurately model the motion of the planet Mars (during which he laid the foundations of modern integral calculus) he concluded that the planets follow not circular orbits, but elliptical orbits with the Sun at one focus of the ellipse. This breakthrough overturned a millennium of dogma based on Ptolemy's idea of "perfect" circular orbits for the "perfect" heavenly bodies. Kepler then went on to formulate his three laws of planetary motion. He also proposed the first known model of planetary motion in which a force emanating from the Sun deflects the planets from their "natural" motion, causing them to follow curved orbits.

During the early 17th century, Galileo pioneered the use of experiment to validate physical theories, which is the key idea in the scientific method. Galileo's use of experiment, and the insistence of Galileo and Kepler that observational results must always take precedence over theoretical results (in which they followed the precepts of Aristotle if not his practice), brushed away the acceptance of dogma, and gave birth to an era where scientific ideas were openly discussed and rigorously tested. Galileo formulated and successfully tested several results in dynamics, including the correct law of accelerated motion, the parabolic trajectory, the relativity of unaccelerated motion, and an early form of the Law of Inertia.

In 1687, Isaac Newton published the *Principia Mathematica,* detailing two comprehensive and successful physical theories: Newton's laws of motion, from which arise classical mechanics; and Newton's Law of Gravitation, which describes the fundamental force of gravity. Both theories agreed well with experiment. Classical mechanics would be exhaustively extended by Lagrange, Hamilton, and others, who produced new formulations, principles, and results. The Law of Gravitation initiated the field of astrophysics, which describes astronomical phenomena using physical theories.

We should include something here about Huygens' observations of Saturn's rings, and his debates with Newton about whether light was a wave or a particle.

18th century

From the 18th century onwards, thermodynamics was developed by Boyle, Young, and many others. In 1733, Daniel Bernoulli used statistical arguments with classical mechanics to derive thermodynamic results, initiating the field of statistical mechanics. In 1798, Thompson demonstrated the conversion of mechanical work into heat.

19th century

In a letter to the Royal Society in 1800, Alessandro Volta described his invention of the electric battery, thus providing for the first time the means to generate a constant electric current, and opening up a new field of physics for investigation.

In 1847 Joule stated the law of conservation of energy, in the form of heat as well as mechanical energy. However, the principle of conservation of energy had been suggested or enunciated in various forms by perhaps a dozen German, French, British and other scientists during the first half of the 19th Century.

The behavior of electricity and magnetism was studied by Faraday, Ohm, and others. Faraday, who began his career in chemistry working under Humphrey Davy at the Royal Institution, demonstrated that electrostatic phenomena, the action of the newly discovered electric pile or battery, electrochemical phenomena, and lightning were all different manifestations of electrical phenomena. Faraday further discovered in 1821 that electricity can cause rotational mechanical motion, and in 1831 discovered the principle of electromagnetic induction, by which means mechanical motion is converted into electricity. Thus it was Faraday who laid the foundations for both the electric motor and the electric generator.

In 1855, Maxwell unified the two phenomena into a single theory of electromagnetism, described by Maxwell's equations. A prediction of this theory was that light is an electromagnetic wave. A more subtle part of Maxwell's deduction was that the observed speed of light does not depend on the speed of the observer, a premonition of the development of special relativity by Einstein.

In 1887 the Michelson-Morley experiment is conducted and it is interpertated as counter to the general held theory of the day, that the Earth was moving through a "luminiferous aether". The development of what later became Einstein's Special Theory of Relativity provided a complete explanation which did not require an aether, and was consistent with the results of the experiment. Michelson and Morely are not convinced of the non-existence of the aether. Morely goes on to conduct experiments with Miller.

In 1887, Tesla investigates X-rays using his own devices as well as Crookes tubes. In 1895, Röntgen observes and analysies X-rays, which turned out to be high-frequency electromagnetic radiation. Radioactivity was discovered in 1896 by Henri Becquerel, and further studied by the Pierre Curie and Marie Curie and others. This initiated the field of nuclear physics.

In 1897, Thomson studies the electron, the elementary particle which carries electrical current in circuits. He deduces that cathode rays existed and were negatively charged "*particles*", which he called "*corpuscles*".

20th century

The beginning of the 20th century brought the start of a revolution in physics. The long-held theories of Newton were shown not to be correct in all circumstances. Not only did quantum mechanics show that the laws of motion didn't hold on small scales, but even more disturbingly, general relativity showed that the fixed background of spacetime, on which both Newtonian mechanics and special relativity depended, could not exist.

In 1904, Thomson proposed the first model of the atom, known as the plum pudding model. (The existence of the atom had been proposed in 1808 by Dalton.)

In 1905, Einstein formulated the theory of special relativity, unifying space and time into a single entity, spacetime. Relativity prescribes a different transformation between reference frames than classical mechanics, necessitating the development of relativistic mechanics as a replacement for classical mechanics. In the regime of low (relative) velocities, the two theories agree. In 1915, Einstein extended special relativity to explain gravity with the general theory of relativity, which replaces Newton's law of gravitation. In the regime of low masses and energies, the two theories agree.

In 1911, Rutherford deduced from scattering experiments the existence of a compact atomic nucleus, with positively charged constituents dubbed protons. Neutrons, the neutral nuclear constituents, were discovered in 1932 by Chadwick.

Beginning in 1900, Planck, Einstein, Bohr, and others developed quantum theories to explain various anomalous experimental results by introducing discrete energy levels. In 1925, Heisenberg and Schrödinger formulated quantum mechanics, which explained the preceding quantum theories. In quantum mechanics, the outcomes of physical measurements are inherently probabilistic. The theory describes the calculation of these probabilities. It successfully describes the behavior of matter at small distance scales.

Quantum mechanics also provided the theoretical tools for condensed matter physics, which studies the physical behavior of solids and liquids, including phenomena such as crystal structures, semiconductivity, and superconductivity. The pioneers of condensed matter physics include Bloch, who created a quantum mechanical description of the behavior of electrons in crystal structures in 1928.

In 1929, Edwin Hubble published his discovery that the speed at which galaxies recede positively correlates with their distance. This is the basis for understanding that the universe is expanding.

In 1937, Tesla challenges Einstein's theory of relativity, announcing a *dynamic theory of gravity* and argue that a field of force was a better concept and did away with the curvature of space. Unfortunately the theory was never published, but Tesla may have been developing a theory about gravity waves.

During World War II, research was conducted by each side into nuclear physics, for the purpose of creating a nuclear bomb. The German effort, led by Heisenberg, did not succeed, but the Allied Manhattan Project reached its goal. In America, a team led by Fermi achieved the first man-made nuclear chain reaction in 1942, and in 1945 the world's first nuclear explosive was detonated in Alamagordo, New Mexico.

Quantum field theory was formulated in order to extend quantum mechanics to be consistent with special relativity. It achieved its modern form in the late 1940s with work by Feynman, Schwinger, Tomonaga, and Dyson. They formulated the theory of quantum electrodynamics, which describes the electromagnetic interaction.

Quantum field theory provided the framework for modern particle physics, which studies fundamental forces and elementary particles. In 1954, Yang and Mills developed a class of gauge theories, which provided the framework for the Standard Model. The Standard Model, which was completed in the 1970s, successfully describes almost all elementary particles observed to date.

Developments since 1990

Attempts to unify quantum mechanics and general relativity made signficant progress during the 1990s. At the close of the century, a Theory of everything was still not in hand, but some of its characteristics were taking shape. Loop quantum gravity, string theory, and black hole thermodynamics all predicted quantized spacetime on the Planck scale.

please add to this

Developments since 2000

Gravity was shown to propagate at the speed of light, confirming one prediction of loop quantum gravity.

Home | Physicists

Physicist

A **physicist** is a scientist trained in physics. Physicists are employed by universities as professors, lecturers, researchers, and by laboratories in industry. Employment as a professional physicist generally requires a doctoral degree. However, many people who have trained as physicsts use their skills in other parts of the economy, in particular in computing and finance.

See also:

- Nobel Prize in physics
- Famous Physicists

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List of physicists

Many famous physicists of the 20th and 21st century are found on the list of recipients of the Nobel Prize in physics.

Famous early physicists:

- Democritus - Abdera (circa 460 BC - 360 BC)
- Archimedes - Syracuse (circa 287 BC - 212 BC)
- Lucretius - Rome (98?-55 BC)
- William Gilbert - England (1544-1603)
- Galileo Galilei - Italy (1564-1642)
- Willebrord Snell - Netherlands (1580-1626)
- René Descartes - France (1596-1650)
- Evangelista Torricelli - Italy (1608-1647)
- Blaise Pascal - France (1623-1662)

- Robert Boyle - England (1627-1691)
- Christian Huygens, (1629-1695)
- Robert Hooke - England (1635-1703)
- Isaac Newton - England (1642-1727)

Famous physicists of the 18th century:

- Daniel Gabriel Fahrenheit, Poland, England, Netherlands(1686-1736)
- Daniel Bernoulli - Switzerland (1700-1782)
- Benjamin Franklin, USA (1706-1790)
- Leonard Euler, (1707-1783)
- Rudjer Josip Boscovich - Dubrovnik (1711-1787)
- Jean Le Rond d'Alembert - France (1717-1783)
- Henry Cavendish - Britain (1731-1810)
- Charles Augustin de Coulomb, (1736-1806)
- Joseph-Louis Lagrange, (1736-1813)
- James Watt Scotland (1736-1819)

Famous physicists of the 19th century:

- Alessandro Volta - Italy (1745-1827)
- Ernst Chladni - Germany (1756-1827)
- John Dalton - England (1766-1844)
- Joseph Fourier, (1768-1830)
- Thomas Young - England (1773-1829)
- Jean-Baptist Biot, (1774-1862)
- Andre Marie Ampere, (1775-1836)
- Amedeo Avogadro - Italy (1776-1856)
- Carl Friedrich Gauss - Germany (1777-1855)
- Hans Christian Ørsted - Denmark (1777-1851)
- Joseph Louis Gay-Lussac - France (1778-1850)
- David Brewster - Scotland (1781-1868)
- William Prout - England (1785-1850)
- Joseph von Fraunhofer Germany (1787-1826)
- Augustin-Jean Fresnel - France (1788-1827)
- Georg Ohm - Germany (1789-1854)
- Michael Faraday - Britain (1791-1867)
- Felix Savart - France (1791-1841)
- Nicolas Léonard Sadi Carnot - France (1796-1832)
- Joseph Henry - USA (1797-1878)
- Christian Doppler - Austria (1803-1853)
- Wilhelm Weber, (1804-1891)
- William Hamilton - Ireland (1805-1865)
- Anders Jonas Ångström, - Sweden(1814-1874)
- James Prescott Joule - Britain (1818-1889)
- Hippolyte Fizeau - France (1819-1896)
- Léon Focault - France (1819-1868)
- George Gabriel Stokes - Britain (1819-1903)

- Hermann von Helmholtz - Germany (1821-1894)
- Rudolf Clausius - Germany (1822-1888)
- Gustav Robert Kirchhoff, (1824 - 1887)
- Johann Jakob Balmer - Switzerland (1825-1898)
- William Thomson - (Lord Kelvin) England (1824-1907)
- Joseph Wilson Swan, (1828-1914)
- James Clerk Maxwell - Britain (1831-1879)
- Jožef Stefan - Austria-Hungary, Slovenia (1835-1893)
- Ernst Mach - Austria (1838-1916)
- Josiah Gibbs, (1839-1903)
- Ernst Abbe - Germany (1840-1905)
- Marie Alfred Cornu, (1841-1902)
- James Dewar - Britain (1842-1923)
- Osborne Reynolds - Britain (1842-1912)
- Ludwig Boltzmann - Austria (1844-1906)
- Roland Eötvös - Hungary (1848-1919)
- Oliver Heaviside - Britain (1850-1925)
- George Francis FitzGerald - Ireland (1851-1901)
- John Henry Poynting - Britain (1852-1914)
- Henri Poincaré, (1854-1912)
- Janne Rydberg, Sweden (1854-1919)
- Edwin Hall - USA (1855-1938)
- Joseph John Thomson, England (1856-1940)
- Heinrich Rudolf Hertz - Germany (1857-1894)
- Aleksandr Mikhailovich Lyapunov - Imperial Russia (1857-1918)

Famous physicists of the 20th century:

- Hannes Alfven - Sweden (1908-1995)
- Henri Becquerel - France (1852-1908)
- John Stewart Bell - Britain (1928-1990)
- Felix Bloch - Switzerland (1905-1983)
- Niels Bohr - Denmark (1885-1962)
- Max Born - Germany, Britain (1882-1970)
- Satyendra Nath Bose - India (1894-1974)
- Louis-Victor de Broglie - France (1892-1987)
- Thomas Townsend Brown - American (1905 - 1985)
- Marie Curie - Poland (1867-1934)
- Fritjof Capra - Austria, USA (1939-)
- Pavel Alekseyevich Cherenkov - Imperial Russia, Soviet union (1904-1990)
- Paul Adrien Maurice Dirac - Britain (1902-1984)
- Freeman Dyson - Britain, USA (1923-)
- Paul Ehrenfest - Austria (1880-1933)
- Albert Einstein - Germany, USA (1879-1955)
- Enrico Fermi - Italy (1901-1954)
- Richard Feynman - USA (1918-1988)

- Vladimir Aleksandrovich Fock - Imperial Russia, Soviet union (1898-1974)
- Murray Gell-Mann - USA (1929-)
- Werner Karl Heisenberg - Germany (1901-1976)
- Stephen Hawking - England (1942-)
- Edwin Jaynes - USA (1922-1998)
- Lev Davidovich Landau - Imperial Russia, Soviet union (1908-1968)
- Irving Langmuir - USA (1851-1957)
- Leonid Isaakovich Mandelshtam - Imperial Russia, Soviet union (1879-1944)
- John von Neumann - Austria-Hungary, USA (1903-1957)
- Robert Oppenheimer - USA (1904-1967)
- Wolfgang Ernst Pauli - Austria (1900-1958)
- Max Planck - Germany (1858-1947)
- John Polkinghorne - Britain (1930-)
- Wilhelm Conrad Röntgen - Germany (1845-1923)
- Ernest Rutherford - New Zealand, England (1871-1937)
- Andrei Dmitrievich Sakharov - Soviet Union (1929-1989)
- Erwin Schrödinger, (1887-1961)
- Igor Yevgenyevich Tamm - Imperial Russia, Soviet union (1895-1971)
- Nikola Tesla - Austria-Hungary, USA (1856-1943)
- Steven Weinberg - USA (1933-)
- Arthur Wightman - USA
- Eugene Wigner - Austria-Hungary, USA (1902-1993)
- Victor Frederick Weisskopf - Austria, USA (1908-2002)

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Nobel Prize in Physics

List of Nobel Prize laureates in physics 1901-2002.
1900s - 1910s - 1920s - 1930s - 1940s - 1950s - 1960s - 1970s - 1980s - 1990s - 2000s

1900s

- 1901
  - Wilhelm Conrad Röntgen
  - "in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"
- 1902
  - Hendrik Antoon Lorentz and Pieter Zeeman
  - "in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena"
- 1903
  - Antoine Henri Becquerel

  - "in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"
  - Pierre and Marie Curie
  - "in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"
- 1904
  - Lord Rayleigh (John William Strutt)
  - "for his investigations of the densities of the most important gases and for his discovery of argon in connection with these studies"
- 1905
  - Philipp Eduard Anton von Lenard
  - "for his work on cathode rays"
- 1906
  - Sir Joseph John Thomson
  - "in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"
- 1907
  - Albert Abraham Michelson
  - "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"
- 1908
  - Gabriel Lippmann
  - "for his method of reproducing colours photographically based on the phenomenon of interference"
- 1909
  - Guglielmo Marconi and Karl Ferdinand Braun
  - "in recognition of their contributions to the development of wireless telegraphy"

1910s

- 1910
  - Johannes Diderik van der Waals
  - "for his work on the equation of state for gases and liquids"
- 1911
  - Wilhelm Wien
  - "for his discoveries regarding the laws governing the radiation of heat"
- 1912
  - Nils Gustaf Dalén
  - "for his invention of automatic regulators for use in conjunction with gas accumulators for illuminating lighthouses and buoys"
- 1913
  - Heike Kamerlingh-Onnes

  - "for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"
- 1914
  - Max von Laue
  - "for his discovery of the diffraction of X-rays by crystals"
- 1915
  - Sir William Henry Bragg and William Lawrence Bragg
  - "for their services in the analysis of crystal structure by means of X-rays"
- 1916
  - The prize money was allocated to the Special Fund of this prize section.
- 1917
  - Charles Glover Barkla
  - "for his discovery of the characteristic Röntgen radiation of the elements"
- 1918
  - Max Planck
  - "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"
- 1919
  - Johannes Stark
  - "for his discovery of the Doppler effect in canal rays and the splitting of spectral lines in electric fields"

1920s

- 1920
  - Charles Edouard Guillaume
  - "in recognition of the service he has rendered to precision measurements in Physics by his discovery of anomalies in nickel steel alloys"
- 1921
  - Albert Einstein
  - "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"
- 1922
  - Niels Henrik David Bohr
  - "for his services in the investigation of the structure of atoms and of the radiation emanating from them"
- 1923
  - Robert Andrews Millikan
  - "for his work on the elementary charge of electricity and on the photoelectric effect"
- 1924
  - Karl Manne Georg Siegbahn

  - "for his discoveries and research in the field of X-ray spectroscopy"
- 1925
  - James Franck and Gustav Ludwig Hertz
  - "for their discovery of the laws governing the impact of an electron upon an atom"
- 1926
  - Jean Baptiste Perrin
  - "for his work on the discontinuous structure of matter, and especially for his discovery of sedimentation equilibrium"
- 1927
  - Arthur Holly Compton
  - "for his discovery of the effect named after him"
  - Charles Thomson Rees Wilson
  - "for his method of making the paths of electrically charged particles visible by condensation of vapour"
- 1928
  - Owen Willans Richardson
  - "for his work on the thermionic phenomenon and especially for the discovery of the law named after him"
- 1929
  - Prince Louis-Victor Pierre Raymond de Broglie
  - "for his discovery of the wave nature of electrons"

1930s

- 1930
  - Sir Chandrasekhara Venkata Raman
  - "for his work on the scattering of light and for the discovery of the effect named after him"
- 1931
  - The prize money was allocated to the Special Fund of this prize section.
- 1932
  - Werner Karl Heisenberg
  - "for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen"
- 1933
  - Erwin Schrödinger and Paul Adrien Maurice Dirac
  - "for the discovery of new productive forms of atomic theory"
- 1934
  - The prize money was with 1/3 allocated to the Main Fund and with 2/3 to the Special Fund of this prize section.
- 1935
  - James Chadwick
  - "for the discovery of the neutron"

- 1936
    - Victor Franz Hess
    - "for his discovery of cosmic radiation"
    - Carl David Anderson
    - "for his discovery of the positron"
- 1937
    - Clinton Joseph Davisson and George Paget Thomson
    - "for their experimental discovery of the diffraction of electrons by crystals"
- 1938
    - Enrico Fermi
    - "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"
- 1939
    - Ernest Orlando Lawrence
    - "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

1940s

- 1940
    - The prize money was with 1/3 allocated to the Main Fund and with 2/3 to the Special Fund of this prize section.
- 1941
    - The prize money was with 1/3 allocated to the Main Fund and with 2/3 to the Special Fund of this prize section.
- 1942
    - The prize money was with 1/3 allocated to the Main Fund and with 2/3 to the Special Fund of this prize section.
- 1943
    - Otto Stern
    - "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"
- 1944
    - Isidor Isaac Rabi
    - "for his resonance method for recording the magnetic properties of atomic nuclei"
- 1945
    - Wolfgang Pauli
    - "for the discovery of the Exclusion Principle, also called the Pauli principle"
- 1946
    - Percy Williams Bridgman

  - "for the invention of an apparatus to produce extremely high pressures, and for the discoveries he made therewith in the field of high pressure physics"
- 1947
  - Sir Edward Victor Appleton
  - "for his investigations of the physics of the upper atmosphere especially for the discovery of the so-called Appleton layer"
- 1948
  - Patrick Maynard Stuart Blackett
  - "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation"
- 1949
  - Hideki Yukawa (oÝ À9)
  - "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"

1950s

- 1950
  - Cecil Frank Powell
  - "for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"
- 1951
  - Sir John Douglas Cockcroft and Ernest Thomas Sinton Walton
  - "for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"
- 1952
  - Felix Bloch and Edward Mills Purcell
  - "for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith"
- 1953
  - Frits (Frederik) Zernike
  - "for his demonstration of the phase contrast method, especially for his invention of the phase contrast microscope"
- 1954
  - Max Born
  - "for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction"
  - Walther Bothe
  - "for the coincidence method and his discoveries made therewith"
- 1955
  - Willis Eugene Lamb
  - "for his discoveries concerning the fine structure of the hydrogen spectrum"

- Polykarp Kusch
- "for his precision determination of the magnetic moment of the electron"

- 1956
  - William Bradford Shockley, John Bardeen, and Walter Houser Brattain
  - "for their researches on semiconductors and their discovery of the transistor effect"
- 1957
  - Chen Ning Yang (J/ç Pinyin: Yáng Zhènníng) and Tsung-Dao Lee (N?S Pinyin: LĐ Zhèngdào)
  - "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"
- 1958
  - Pavel Alekseyevich Cherenkov (025; ;5:A5528G '5@5=:>2), Il'ia Frank (;LO 8E09;>28G $@0=:), and Igor Yevgenyevich Tamm (3>@L 235=L528G "0)
  - "for the discovery and the interpretation of the Cherenkov-Vavilov effect"
- 1959
  - Emilio Gino Segre and Owen Chamberlain
  - "for their discovery of the antiproton"

1960s

- 1960
  - Donald Arthur Glaser
  - "for the invention of the bubble chamber"
- 1961
  - Robert Hofstadter
  - "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"
  - Rudolf Ludwig Mössbauer
  - "for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"
- 1962
  - Lev Davidovich Landau (52 0284>28G 0=40C)
  - "for his pioneering theories for condensed matter, especially liquid helium"
- 1963
  - Eugene Paul Wigner
  - "for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"
  - Maria Goeppert-Mayer and J. Hans D. Jensen

  - "for their discoveries concerning nuclear shell structure"
- 1964
  - Charles Hard Townes, Nicolay Gennadiyevich Basov (8:>;09 5==048528G 0A>2), and Aleksandr Mikhailovich Prokhorov (;5:A0=4@ 8E09;>28G @>E>@>2)
  - "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"
- 1965
  - Sin-Itiro Tomonaga (8 /Î), Julian Schwinger, and Richard P. Feynman
  - "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"
- 1966
  - Alfred Kastler
  - "for the discovery and development of optical methods for studying Hertzian resonances in atoms"
- 1967
  - Hans Albrecht Bethe
  - "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"
- 1968
  - Luis Walter Alvarez
  - "for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis"
- 1969
  - Murray Gell-Mann
  - "for his contributions and discoveries concerning the classification of elementary particles and their interactions"

1970s

- 1970
  - Hannes Olof Gösta Alfvén
  - "for fundamental work and discoveries in magneto-hydrodynamics with fruitful applications in different parts of plasma physics"
  - Louis Eugene Félix Néel
  - "for fundamental work and discoveries concerning antiferromagnetism and ferrimagnetism which have led to important applications in solid state physics"
- 1971
  - Dennis Gabor
  - "for his invention and development of the holographic method"

- 1972
  - John Bardeen, Leon Neil Cooper, and John Robert Schrieffer
  - "for their jointly developed theory of superconductivity, usually called the BCS-theory"
- 1973
  - Leo Esaki (_ ²¼H) and Ivar Giaever
  - "for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"
  - Brian David Josephson
  - "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"
- 1974
  - Sir Martin Ryle and Antony Hewish
  - "for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"
- 1975
  - Aage Niels Bohr, Ben Roy Mottelson, and Leo James Rainwater
  - "for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection"
- 1976
  - Burton Richter and Samuel Chao Chung Ting (‡- Pinyin: D+ng ZhàozhMng)
  - "for their pioneering work in the discovery of a heavy elementary particle of a new kind"
- 1977
  - Philip Warren Anderson, Sir Nevill Francis Mott, and John Hasbrouck van Vleck
  - "for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems"
- 1978
  - Pyotr Leonidovich Kapitsa (5B@ 5>=84>28G 0?8F0)
  - "for his basic inventions and discoveries in the area of low-temperature physics"
  - Arno Allan Penzias and Robert Woodrow Wilson
  - "for their discovery of cosmic microwave background radiation"
- 1979
  - Sheldon Lee Glashow, Abdus Salam, and Steven Weinberg
  - "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

1980s

- 1980
  - James Watson Cronin and Val Logsdon Fitch
  - "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"
- 1981
  - Nicolaas Bloembergen and Arthur Leonard Schawlow
  - "for their contribution to the development of laser spectroscopy"
  - Kai Manne Boerje Siegbahn
  - "for his contribution to the development of high-resolution electron spectroscopy"
- 1982
  - Kenneth G. Wilson
  - "for his theory for critical phenomena in connection with phase transitions"
- 1983
  - Subrahmanyan Chandrasekhar
  - "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars"
  - William Alfred Fowler
  - "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"
- 1984
  - Carlo Rubbia and Simon van der Meer
  - "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"
- 1985
  - Klaus von Klitzing
  - "for the discovery of the quantized Hall effect"
- 1986
  - Ernst Ruska
  - "for his fundamental work in electron optics, and for the design of the first electron microscope"
  - Gerd Binnig and Heinrich Rohrer
  - "for their design of the scanning tunneling microscope"
- 1987
  - J. Georg Bednorz and K. Alexander Müller
  - "for their important break-through in the discovery of superconductivity in ceramic materials"
- 1988
  - Leon M. Lederman, Melvin Schwartz, and Jack Steinberger
  - "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

- 1989
  - Norman F. Ramsey
  - "for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"
  - Hans G. Dehmelt and Wolfgang Paul
  - "for the development of the ion trap technique"

1990s

- 1990
  - Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor
  - "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"
- 1991
  - Pierre-Gilles de Gennes
  - "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers"
- 1992
  - Georges Charpak
  - "for his invention and development of particle detectors, in particular the multiwire proportional chamber"
- 1993
  - Russell A. Hulse and Joseph H. Taylor Jr.
  - "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"
- 1994
  - "for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter"
  - Bertram N. Brockhouse
  - "for the development of neutron spectroscopy"
  - Clifford G. Shull
  - "for the development of the neutron diffraction technique"
- 1995
  - "for pioneering experimental contributions to lepton physics"
  - Martin L. Perl
  - "for the discovery of the tau lepton"
  - Frederick Reines
  - "for the detection of the neutrino"
- 1996
  - David M. Lee, Douglas D. Osheroff, and Robert C. Richardson
  - "for their discovery of superfluidity in helium-3"

- 1997
  - Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips
  - "for development of methods to cool and trap atoms with laser light"
- 1998
  - Robert B. Laughlin, Horst L. Störmer, and Daniel C. Tsui
  - "for their discovery of a new form of quantum fluid with fractionally charged excitations"
- 1999
  - Gerardus 't Hooft and Martinus J.G. Veltman
  - "for elucidating the quantum structure of electroweak interactions in physics"

2000s

- 2000
  - Zhores Ivanovich Alferov (>@5A 20=>28G ;D5@>2)
  - "for basic work on information and communication technology"
  - Herbert Kroemer
  - "for developing semiconductor heterostructures used in high-speed- and opto-electronics"
  - Jack S. Kilby
  - "for his part in the invention of the integrated circuit"
- 2001
  - Eric Allin Cornell, Wolfgang Ketterle, and Carl Edwin Wieman
  - "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"
- 2002
  - Raymond Davis Jr. and Masatoshi Koshiba (ô Ê)
  - "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
  - Riccardo Giacconi
  - "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"
- 2003
  - Alexei Alexeevich Abrikosov (;5:A59 ;5:A5528G 1@8:>A>2), Vitaly Lazarevich Ginzburg (8B0;89 070@528G 8=71C@3) and Anthony James Leggett
  - "for pioneering contributions to the theory of superconductors and superfluids"

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Unsolved problems in physics

The following is an incomplete list of outstanding problems in physics. Some of these problems are theoretical, meaning that existing theories seem incapable of explaining some observed phenomenon or experimental result. Others are experimental, meaning that there is a difficulty in creating an experiment to test a proposed theory or investigate a phenomenon in greater detail.

- Accretion disc jets. Why do the accretion discs surrounding certain astronomical objects, such as the nuclei of active galaxies, emit radiation jets along their polar axes?
- Amorphous solids. What is the nature of the transition between a fluid or regular solid and a glassy phase? What are the microscopic physics giving rise to the general properties of glasses?
- Fusion power. Is it possible to construct a practical nuclear reactor that is powered by the nuclear fusion rather than nuclear fission?
- Galaxy rotation problem. Why do galaxies rotate at speeds inconsistent with their apparent mass?
- Gamma ray bursters. What is the nature of these extraordinarily energetic astronomical objects?
- Gravitational waves. Is it possible to construct a device to detect the gravitational waves emitted by, for example, a pair of inspiralling neutron stars? Such a device would be invaluable for observational astronomy.
- GZK paradox. Why is it that some cosmic rays appear to possess energies that are impossibly high, given that there are no sufficiently energetic cosmic ray sources near the Earth, and cosmic rays emitted by distant sources should have been absorbed by the cosmic microwave background radiation?
- High-temperature superconductors. Why do certain materials exhibit superconductivity at temperatures much higher than 20K?
- Magnetic monopoles. Are there any particles that carry "magnetic charge", and if so, why are they so difficult to detect?
- Quantum chromodynamics (QCD) in the non-perturbative regime. The equations of QCD remain unsolved at energy scales relevant for describing atomic nuclei. How does QCD give rise to the physics of nuclei and nuclear constituents?
- Quantum computers. Is it possible to construct a practical computer that performs calculations on qubits (quantum bits)?
- Quantum gravity. How can the theory of quantum mechanics be merged with the theory of general relativity? Does our present understanding of the gravitational force remain correct at microscopic length scales?
- Quantum mechanics in the correspondence limit. Is there a preferred interpretation of quantum mechanics? How does the quantum description of reality, which includes elements such as the superposition of states and wavefunction collapse, give rise to the reality we perceive?
- Spintronics. Is it possible to construct a practical electronic device that operates on the spin of the electron, rather than its charge?

- Standard Model parameters. What gives rise to the Standard Model of particle physics? Why do its particle masses and coupling constants possess the values we have measured? Does the Higgs boson predicted by the model really exist?
- Supersymmetry. Is supersymmetry a symmetry of Nature? If so, how is supersymmetry broken, and why?
- Theory of Everything -does it exist, how does it relate to everything, and how does it effect us?
- Time Travel. Is it possible?
- Turbulence. Is it possible to make a theoretical model to describe the behavior of a turbulent fluid (in particular, its internal structures)?
- Why are we here?

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Related fields

Home | Astronomy & Astrophysics | Biophysics | Electronics | Engineering | Geophysics | Materials Science | Mathematical Physics | Medical Physics | Physical Chemistry | Philosophy of Physics

Astronomy

Astronomy, which etymologically means "*law of the stars*", is a science involving the observation and explanation of events occurring outside Earth and its atmosphere. Astronomy is often associated with astrophysics.

Astronomy is one of the few sciences where amateurs still play an active role, especially in the discovery and monitoring of transient phenomena. This is not to be confused with astrology, a pseudoscience which attempts to predict a person's destiny by tracking the paths of astronomical objects. Although the two fields share a common origin, they are quite different; astronomy embraces the scientific method, while astrology, with no basis in science, does not.

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Divisions of astronomy

Given its huge scope, astronomy is divided into different branches. A first main distinction is between *theoretical* and *observational* astronomy. *Observers* use a variety of means to obtain data about different phenomena, data that is then used by *theorists* to create and constrain theories and models, to explain observations and to predict new ones. Fields of study are also categorized in another two ways: by *subject*, usually according to the region of space (e.g. Galactic astronomy) or *problems addressed* (such as star formation or cosmology).

By subject

- Amateur astronomy
- Astrometry
- Observational cosmology
- Galactic astronomy
- Extragalactic astronomy
- Galaxy formation and evolution
- Positional astronomy
- Star formation
- Stellar evolution
- Stellar astronomy
- Astrophysics - theoretical astrophysics
- cosmosophy
- cosmogony

Ways of obtaining information

In astronomy, the main way of obtaining information is through the detection and analysis of electromagnetic radiation, photons, but information is also carried by cosmic rays, neutrinos, and, in the near future, gravitational waves (see LIGO and LISA).

A traditional division of astronomy is given by the region of the electromagnetic spectrum observed:

- Optical astronomy refers to the techniques used to detect and analyze light in and slightly around the wavelengths than can be detected with the eyes (about 400 - 800 nm). The most common tool is the telescope, with electronic imagers and spectrographs.
- Infrared astronomy deals with the detection of infrared radiation (wavelengths longer than red light). The most common tool is the telescope but with the instrument optimized for infrared. Space telescopes are also used to eliminate noise (electromagnetic interference) from the atmosphere.
- Radio astronomy uses completely different instruments to detect radiation of wavelengths of mm to cm. The receivers are similar to those used in radio broadcast transmission (which uses those wavelengths of radiation). See also Radio telescopes.
- High-energy astronomy

Optical and radio astronomy can be performed with ground-based observatories, because the atmosphere is transparent at those wavelengths. Infrared light is heavily absorbed by water vapor, so infrared observatories have to be located in high, dry places or in space.

The atmosphere is opaque at the wavelengths used by X-ray astronomy, gamma-ray astronomy, UV astronomy and, except for a few wavelength "windows", Far infrared

astronomy , and so observations can be carried out only from balloons or space observatories.

Short history

In the early part of its history, astronomy involved only the observation and predictions of the motions of the objects in the sky that could be seen with the naked eye. The Rigveda refers to the 27 constellations associated with the motions of the sun and also the 12 zodiacal divisions of the sky. The ancient Greeks made important contributions to astronomy, among them the definition of the magnitude system. The Bible contains a number of statements on the position of the earth in the universe and the nature of the stars and planets, most of which are poetic rather than literal; see Biblical cosmology. In 500 AD, Aryabhata presented a mathematical system that took the earth to spin on its axis and considered the motions of the planets with respect to the sun.

The study of astronomy almost stopped during the middle ages, except for the work of Arabic astronomers. In the late 9th century the Islamic astronomer al-Farghani (Abu'l-Abbas Ahmad ibn Muhammad ibn Kathir al-Farghani) wrote extensively on the motion of celestial bodies. In the 12th century, his works were translated into Latin, and it is said that Dante got his astronomical knowledge from al-Farghani's books.

In the late 10th century, a huge observatory was built near Tehran, Iran, by the astronomer al-Khujandi who observed a series of meridian transits of the Sun, which allowed him to calculate the obliquity of the ecliptic, also known as the tilt of the Earth's axis relative to the Sun. As we know today, the Earth's tilt is approximately 23o34', and al-Khujandi measured it as being 23o32'19". Using this information, he also compiled a list of latitudes and longitudes of major cities.

Omar Khayyam (Ghiyath al-Din Abu'l-Fath Umar ibn Ibrahim al-Nisaburi al-Khayyami) was a great Persian scientist, philosopher, and poet who lived from 1048-1131. He compiled many astronomical tables and performed a reformation of the calendar which was more accurate than the Julian and came close to the Gregorian. An amazing feat was his calculation of the year to be 365.24219858156 days long, which is accurate to the 6th decimal place.

During the renaissance Copernicus proposed a heliocentric model of the Solar System. His work was defended, expanded upon, and corrected by Galileo Galilei and Johannes Kepler. Kepler was the first to devise a system which described correctly the details of the motion of the planets with the Sun at the center. However, Kepler did not understand the reasons behind the laws he wrote down. It was left to Newton's invention of celestial dynamics and his law of gravitation to finally explain the motions of the planets.

Stars were found to be far away objects. With the advent of spectroscopy it was proved that they were similar to our own sun, but with a wide range of temperatures, masses and sizes. The existence of our galaxy, the Milky Way, as a separate group of stars was only proven in the 20th century, along with the existence of "external" galaxies, and soon after, the expansion of the universe seen in the recession of most galaxies from us. Cosmology made huge advances during the 20th century, with the model of the big bang heavily supported by the evidence provided by astronomy and physics, such as the cosmic microwave background radiation, Hubble's Law and cosmological abundances of elements.

Astronomy Tools

- Telescope
- Computers
- Calculator

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Biophysics

Biophysics (also *biological physics*) is an interdisciplinary science that applies theories and methods of the physical sciences to questions of biology. Many of the research traditions in biophysics were initiated by scientists who were doctoral level physicists, although many of the scientists who call themselves biophysicists today were not. Biophysicists work in the areas of physiology, neuroscience, biochemistry and molecular biology.

Topics in biophysics and related fields

- bioenergetics
- cell biophysics
- channels, receptors and transporters
- electrophysiology
- membranes
- muscle and contractility
- nucleic acids
- photobiophysics
- proteins
- supramolecular assemblies
- spectroscopy, imaging etc.
- systems neuroscience
- neural encoding

Notable biophysicists

- Georg von Békésy, research on the human ear, Nobel Prize in Physiology or Medicine, 1961
- Friedrich Dessauer, research on radiation, especially X-rays
- Walter Friedrich widely viewed as a co-founder of biophysics
- Boris Rajewsky
- Maurice Wilkins, co-discover of the structure of DNA, Nobel Prize in Physiology or Medicine, 1962

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Electronics

Electronics is the study and use of electrical devices that operate by controlling the flow of electrons or other electrically charged particles in devices such as thermionic valves and semiconductors. The pure study of such devices is considered as a branch of physics, while the design and construction of electronic circuits to solve practical problems is called electronic engineering.

The main uses of electronic circuits are the controlling, processing and distribution of information, and the conversion and distribution of electrical power. Both of these uses involve the creation or detection of electromagnetic fields and electric currents.

While electricity had been used for some time to transmit data over telegraphs and telephones, the development of electronics truly began in earnest with the advent of radio. Today, electronic devices perform a much wider variety of tasks.

One way of looking at an electronic system is to divide it into the following parts:

1. Inputs - Electrical or mechanical sensors (or transducers), which take signals (in the form of temperature, pressure, etc.) from the physical world and convert them into current/voltage signals.
2. Signal processing circuits - These consist of electronic components connected together to manipulate, interpret and transform the signals.
3. Outputs - Actuators or other devices (also transducers) that transform current/voltage signals back into useful physical form.

Take as an example a television. Its input is a broadcast signal received by an antenna or fed in through a cable. Signal processing circuits inside the television extract the brightness, colour and sound information from this signal. The output devices are a cathode ray tube that converts electronic signals into a visible image on a screen and magnet driven audio speakers.

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8 Photoelectric devices

9 Antennae etc.

10 Analog circuits

11 Digital circuits

12 Mixed-signal circuits

13 Noise

14 Electronics Theory

Electronic Test Equipment

- Ammeter, e.g. Galvanometer (Measure current)
- Ohmmeter, e.g. Wheatstone bridge (Measure resistance)
- Voltmeter (Measures voltage)
- Multimeter (Measures all of the above)
- Logic analyzer (Tests digital circuits)
- Oscilloscope (Measures all of the above as they change over time)
- Electrometer (Measures charge)

Interconnecting Electronic Components

- electrical connectors, plugs and sockets etc.
- printed circuit boards
- integrated circuit
- point-to-point construction
- wire-wrap
- breadboard

Passive Components

- resistor
- capacitor
- inductor
- transformer
- piezoelectric crystal
- magnetic amplifier (toroid)

Active Components (solid-state)

- diode
    - light emitting diode
    - photodiode
    - laser diode
    - Zener diode
    - Schottky diode
    - transient voltage suppression diode
    - variable capacitance diode
- transistor
    - field effect transistor
    - bipolar transistor
    - IGBT transistor
    - Darlington transistor
    - photo transistor
- other active components
    - triac
    - thyristor
    - unijunction transistor
    - varistor
    - Silicon Controlled Rectifier (SCR)

Active Components (thermionic)

- thermionic valve
- cathode ray tube
- klystron
- magnetron

Electromechanical Sensors and Actuators

- microphone
- loudspeaker
- strain gauge
- switch

Thermoelectric devices

- thermistor
- thermocouple
- thermopile
- Peltier cooler

Photoelectric devices

- light-dependent resistor
- photodiode
- photovoltaic cell (solar cell)

Antennae etc.

- radio antenna

Analog circuits

Most analog electronic appliances, such as radio receivers, are constructed from arrays of a few types of circuits.

- Analog computer
- Analog multipliers
- electronic amplifiers
- electronic filters
- electronic oscillators
- electronic mixers
- electronic power supply
- impedance matchers
- operational amplifiers

Digital circuits

Computers, electronic clocks, and programmable logic controllers (used to control industrial processes) are constructed of digital circuits. Digital Signal Processors are another example.

- logic gates
- flip-flops
- counters
- registers
- multiplexers
- microprocessors
- microcontrollers
- DSP

Mixed-signal circuits

Mixed-signal circuits, also known as hybrid circuits, are becoming increasingly common. Mixed circuits contain both analog and digital components. analog to digital converters and digital to analog converters are the primary examples. Other examples are transmission gates and buffers.

Noise

Associated with all electronic circuits is noise. Types of noise include

- Shot noise in resistors.
- Thermal noise in resistors.
- White noise
- Coloured noise

Electronics Theory

- Mathematical Methods of Electronics
- Digital Electronics
- Analog Electronics

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Engineering

Engineering is the application of science to the needs of humanity. This is accomplished through knowledge, mathematics and practical experience applied to the design of useful objects or processes. Its practitioners are called engineers.

Engineers form the bridge between the two distinct worlds of the scientist and the layman. They interpret science for the layman. A scientist asks "Why...?" and thus follows an open-ended research career, whereas an engineer always asks "How...?". That is, he has the problem in hand, knows what solution it requires and tries to find out different ways of implementing it.

There is a difference between an engineer and a technologist though the terms are often used interchangeably. Once an engineer has found a solution for the problem at hand his work stops. The next phase is fine tuning the solution, which is in the domain of the technologist. This process is dependent on various factors which vary with time. A solution which could be a practical application of a scientific fact does not satisfy a technologist. He endeavours to bring it within the economic constraints so that the common man not only understands and marvels at science but also is able to enjoy it and lose his fear of it by constant interaction.

For example, when Edison developed the phonograph it was marveled at. That was engineering. But when he asked his assistant to develop it further so as to remove some harmonics from the sound, that was technology. Because only then could one listen to it and enjoy.

This also explains the time gap between a fact being understood by science, then being implemented by engineers, and then being available from the local shop.

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The task of engineering

The engineer must identify and understand the relevant constraints in order to produce a successful design. Constraints include available resources, physical or technical limitations, flexibility for future modifications and additions, and other factors such as requirements for cost, manufacturability, serviceability, and marketing and aesthetic, social, or ethic considerations. By understanding the constraints, engineers deduce specifications for the limits within which an object or system may be produced and operated. Engineering is therefore a contingent enterprise influenced by many considerations.

Problem solving

Engineers use their knowledge of science and mathematics, and appropriate experience, to find suitable solutions to a problem. Creating an appropriate mathematical model of a problem allows them to analyze it (perhaps, but exceptionally, definitively), and to test potential solutions. If multiple reasonable solutions exist, engineers evaluate the different design choices on their merits and choose the solution that best meets the requirements.

Engineers typically attempt to predict how well their designs will perform to their specifications prior to full-scale production. They use, among other things: prototypes, scale models, simulations, destructive tests, and stress tests. Testing ensures that products will perform as expected. Engineers as professionals take seriously their responsibility to produce designs that will perform as expected and will not cause unintended harm to the public at large. Engineers typically include a factor of safety in their designs to reduce the risk of unexpected failure.

Use of computers

Computers, and design software, play an increasingly important role. Using Computer Aided Design (CAD) software, engineers are able to capture more information about their designs. The computer can automatically translate some models to instructions suitable for automatic machinery (e.g. CNC) to fabricate (part of) a design. The computer also allows increased reuse of previously developed designs by presenting an engineer with a library of predefined parts ready to be used in his own designs.

Etymology

It is a myth that *engineer* originated to describe those who built engines. In fact, the words *engine* and *engineer* (as well as *ingenious*) developed in parallel from the Latin root *ingeniosus*, meaning 'skilled'. An engineer is thus a clever, practical, problem solver. The spelling of *engineer* was later influenced by back-formation from *engine*. The term later evolved to include all fields where the skills of application of the scientific method are used. In other languages like Arabic, the word for "engineering" also means "geometry".

Connections to other disciplines

Science attempts to explain newly observed and unexplained phenomena, often creating mathematical models of observed phenomena. Technology and engineering are attempts at practical application of knowledge (often from science). Scientists work on science; engineers work on technology. However, there is often an overlap between science and engineering. It is not uncommon for scientists to become involved in the practical application of their discoveries; thereby becoming, for the moment, engineers. Conversely, in the process of developing technology engineers sometimes find themselves exploring new phenomena, thus becoming, for the moment, scientists.

There are also close connections between the workings of engineers and artists; they are direct in some fields, eg architecture and industrial design, and indirect in all. Artistic and engineering creativity may be fundamentally connected.

Tools

- Computers
- Calculator

Methods

- Mathematics
- Physics
- Chemistry

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Geophysics

Geophysics, the study of the earth by quantitative physical methods, especially by seismic reflection and refraction, gravity, magnetic, electrical, electromagnetic, and radioactivity methods.

It includes the branches of:

1. Seismology (earthquakes and elastic waves)
2. Gravity and geodesy (the earth's gravitational field and the size and form of the earth)
3. Atmospheric electricity and terrestrial magnetism (including ionosphere, Van Allen belts, telluric currents, etc.)
4. Geothermometry (heating of the earth, heat flow, volcanology, and hot springs)
5. Hydrology (ground and surface water, sometimes including glaciology)
6. Physical oceanography
7. Meteorology
8. Tectonophysics (geological processes in the earth)
9. Exploration and engineering geophysics

A related field is geochemistry.

Exploration geophysics is the use of seismic, gravity, magnetic, electrical and electromagnetic, etc., methods in the search for oil, gas, minerals, water, etc., with the objective of economic exploitation. The Society of Exploration Geophysicists (seg.org) has the most recent update of the sciences and technologies of exploration geophysics. (See also petroleum geology).

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Materials science

Materials science includes those parts of chemistry, physics, geology, and even biology that deal with the physical properties of materials. It is usually considered an applied science, in which the properties under study have some industrial purpose.

Materials science encompasses all classes of materials, the study of each of which may be considered a separate field: metals and metallurgy, ceramics, semiconductors and other electronic materials, polymers, and Biomaterials. Metallurgy and ceramics have long and separate histories as engineering disciplines, but because the science that underlies these disciplines applies to all classes of materials, materials science is recognized as a distinct discipline.

Materials science is related to materials engineering, which tends to focus on processing techniques (casting, rolling, welding, ion implantation, crystal growth, thin-film deposition, sintering, glassblowing, etc.), analytical techniques (electron microscopy, x-ray diffraction, calorimetry, nuclear microscopy (HEFIB) etc.), materials design, and cost/benefit tradeoffs in industrial production of materials.

Core Topics in Materials Science:

Thermodynamics, for phase stability, phase transformations and phase diagrams.
Kinetics, applied to the rates of phase transformations and diffusion.
Crystallography and the use of diffraction techniques for phase identification.
Solid state chemistry, for understanding the synthesis, stucture and phase relationships of solids
Solid-state mechanics, for understanding plastic deformation of solids and fracturing.
Solid-state physics, for understanding electrical properties of materials.
Defects in crystals, such as grain boundaries and dislocations, and their effects on physical properties.

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Mathematical physics

Mathematical physics is the study of physics using mathematics. It might be argued that all of physics is mathematical physics, but in practice, most physics is done on a more intuitive/approximate or even questionable level. Mathematical physics tries to study physics on a more abstract and rigorous level than typical.

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Medical physics

Medical physics concerns the application of physics to medicine. It is generally concerns physics as applied to medical imaging and radiation therapy.

For example, nuclear magnetic resonance (now with the new PC title magnetic resonance imaging), was applied to help look inside people.

Other medical physics applications:

- ultrasound
- Doppler ultrasound
- Radiation protection
- Nuclear Medicine

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Physical chemistry

Physical chemistry is a science field in the crossover between chemistry and physics. Chemical thermodynamics, chemical kinetics , quantum chemistry, statistical mechanics, and spectroscopy are some areas of chemistry comprising the bulk of physical chemistry.

Physical chemistry is also strongly intertwined in the pursuit of materials science.

Important Physical-chemists

- Peter Debye
- J.W. Gibbs
- J.H. van 't Hoff
- B. Težak

Literature

- Physical Chemistry, P.W. Atkins, 1978, Oxford University Press
- Introduction to Modern Colloid Science, R.J. Hunter, 1993, Oxford University Press
- Principles of Colloid and Surface Chemistry, P.C. Hiemenz, R. Rajagopalan, 1997, Marcel Dekker Inc., New York

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Philosophy of physics

Philosophy of physics is the study of the fundamental, philosophical questions underlying modern physics. Perhaps the main questions concern the nature of space and time, atoms and atomism, cosmology, the interpretation of the results of quantum mechanics, the foundations of statistical mechanics, determinism, and the nature of physical laws. Classically, several of the questions of this area were studied as part of metaphysics (for example, those about determinism and space and time). Today, philosophy of physics is very close to philosophy of science.

Subjects in the philosophy of physics:

- Philosophy of quantum mechanics
- Philosophy of space and time
- Philosophy of thermal and statistical physics

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